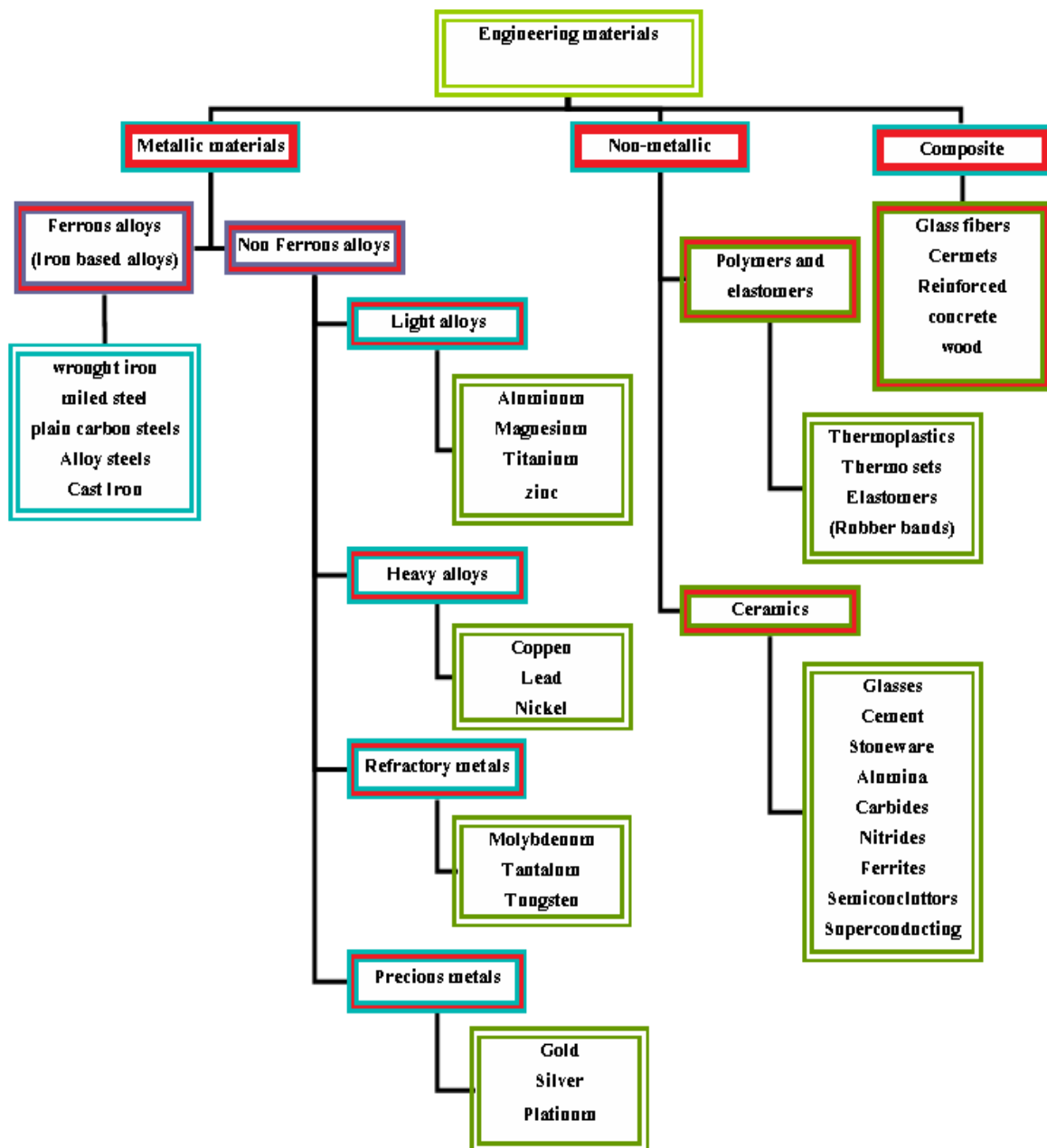


Engineering Materials

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Type of materials

Materials are usually classified into the main and subgroups illustrated as .below :



Basic properties of engineering materials:

The basic properties of materials can be grouped as:

- 1- Physical properties:** these include color, luster, specific gravity, porosity, structure.....etc.
- 2- Mechanical properties:** these include elasticity, plasticity, ductility, brittleness, hardness, toughness, stiffness, and strengthetc.
- 3-Thermal properties:** these include specific heat, thermal conductivity, expansion, latent heat thermal stresses, thermal shock ... etc.
- 4- Electrical properties:** these include conductivity, resistivity, relative capacity, dielectric strength ...etc.
- 5- Chemical properties:** these include atomic weight, equivalent weight, molecule weight, acidity, alkalinity, chemical composition, corrosion, oxidation,...etc .
- 6-Magnetic properties:** these include magnetic permeability, magnetization, magnetic susceptibility.
- 7- Optical properties:** these include refract we index, transmissivity

Crystal Structure:

If we examine a few metallic solid materials under a microscope: we shall find that these materials have a crystalline structure . the example of such material are iron, copper ,aluminum ... etc. There are some other materials ,which do not have crystalline structure.. such materials are called non-crystalline or **amorphous materials**.. The example of such material ,are wood ,plastics ,paper ,glass ...etc .A crystalline material may be either in the form of single crystal or an aggregate of many crystal (known as **polycrystalline**) . the poly crystalline material is always separated by well defined boundaries .

Crystal:

The term **crystal** may be defined as a small body having a regular polyhedral form , bounded by smooth surfaces. The crystals are also known as **grains**. The boundary separating the two adjacent grains , is called grain boundary.

Single Crystal:

The common example of such material are sugar , common salt (**sodium chloride**) **diamond** ,... etc .The single crystals of materials are produced artificially from their vapor or liquid state. These crystals represent a material in its ideal condition.

Crystal Lattice or Space Lattice:

A metal consists of a number of crystals , each crystal is considered from the atoms being arranged in a regular pattern , now if we replace all the atoms , in this cross-section , by points (corresponding to the centers of all the atoms), we shall get a group of points as shown in {fig-1} . These points are known as **lattice points**. Similarly all the atoms of a crystal in three dimensional patterns may be replaced by three dimensional groups of lattice points. This group of a lattice points, in the three dimensional pattern, is known as **crystal lattice** or space lattice as shown in {fig-2} .

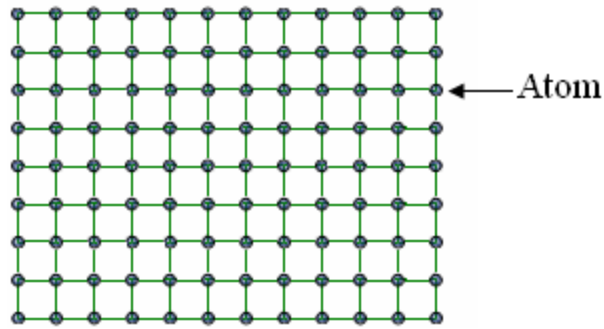


Fig (1) : The cross – section of metal atoms arrangement in part of crystal structure

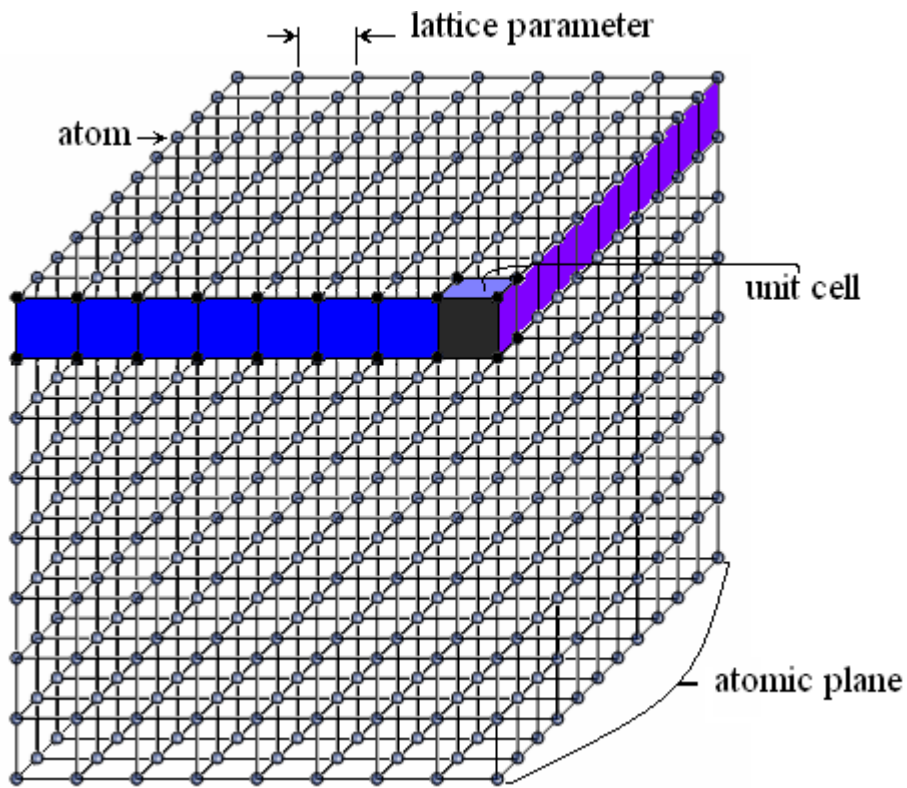


Fig (2) : The shape of a part of crystal in a crystalline material

Unit Cell:

In a crystal system , the atoms or molecules are arranged in a particular fashion , in all the three axis . The smallest part which has same arrangement of its atoms as that of the crystal is called *unit cell*. as shown in {fig- 3}

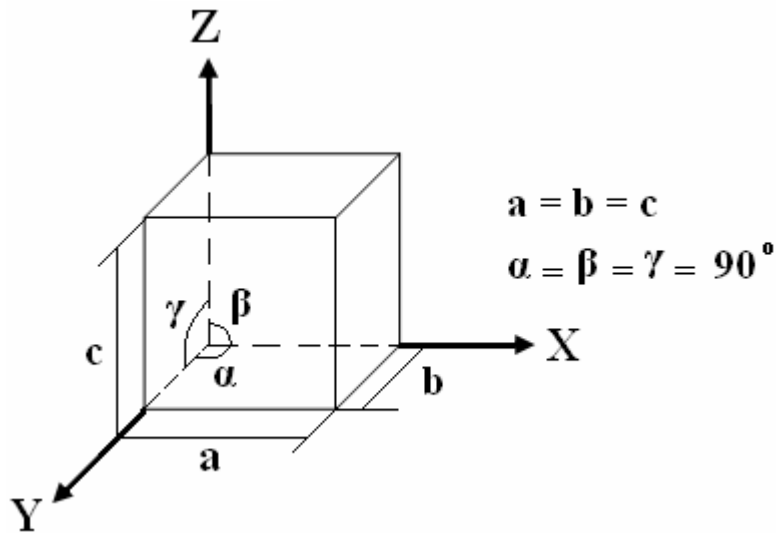


Fig (3) : The shape of a cubic unit cell

Types of Crystal Systems:

The crystal systems may be divided into seven groups or basic systems. These seven basic crystal systems are distinguished from one another by the angles between the three axes and the intercepts of the faces along them. the table -1- shows the seven basic crystal systems along with their characteristics. and {fig-4} shows the fourteen types of unit cells that can describe all possible crystal systems (lattice).

Table :1 The seven basic crystal systems along with their characteristics

System	Axes	Axial angles
Cubic	$a_1 = a_2 = a_3$	All angles = 90°
Tetragonal	$a_1 = a_2 \neq c$	All angles = 90°
Orthohombic	$a \neq b \neq c$	All angles = 90°
Monoclinic	$a \neq b \neq c$	Two angles = 90° ; 1 angle $\neq 90^\circ$
Triclinic	$a \neq b \neq c$	All angles different; none equal 90°
Hexagonal	$a_1 = a_2 = a_3 \neq c$	Angles = 90° and 120°
Rhombohedral	$a_1 = a_2 = a_3$	All angles equal, but not 90°

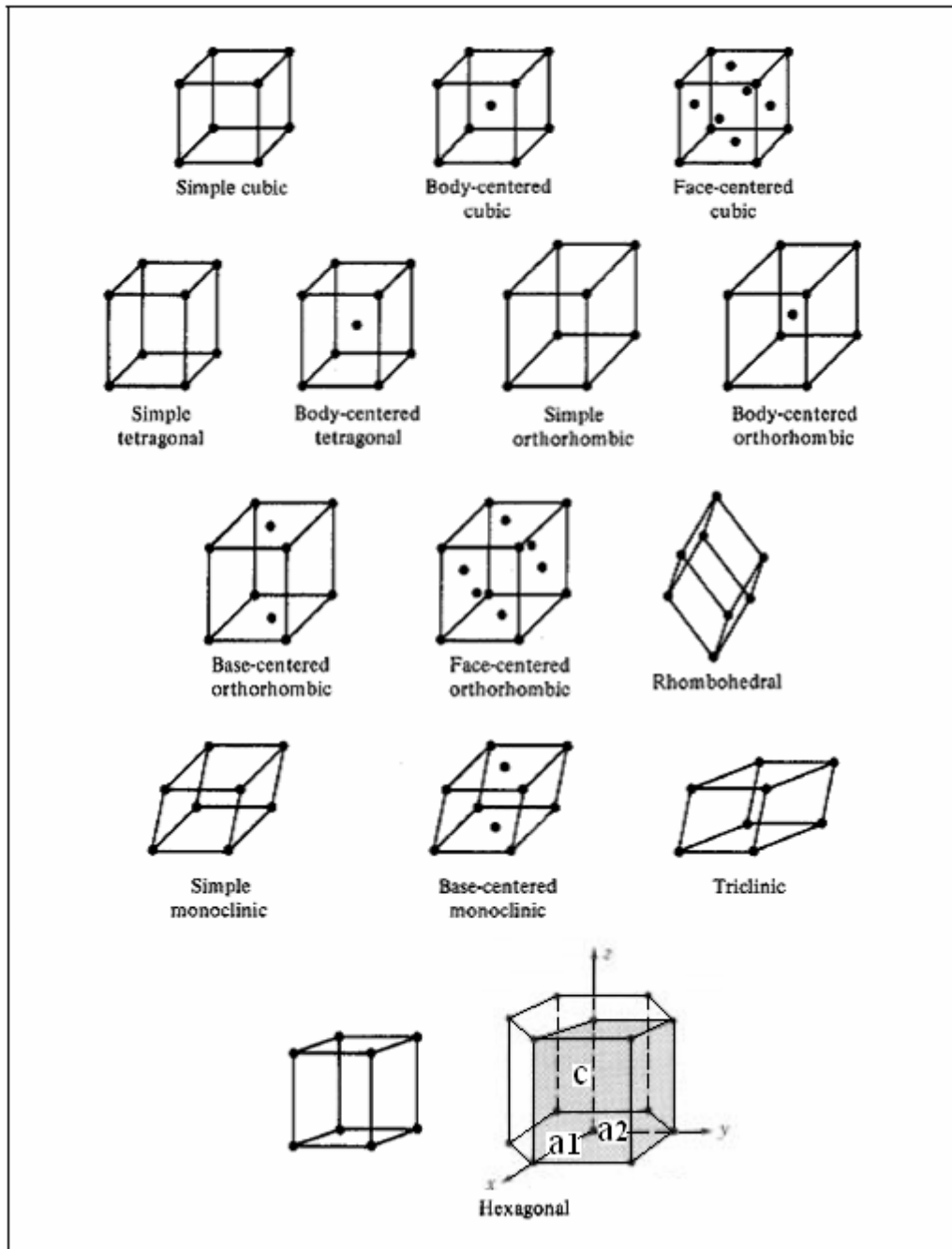


Fig (4) : The fourteen types of unit cells that can describe all possible crystal systems (lattice).

Metallic Structure:

It has been observed that most of the common metals possess *cubic* or *hexagonal structures* only . The unit cell of each different crystal has different placement of atoms , from this point of view following are the types of metallic structures.

1-Cubic Structures :

Body Centered Cubic Structure (BCC): a-

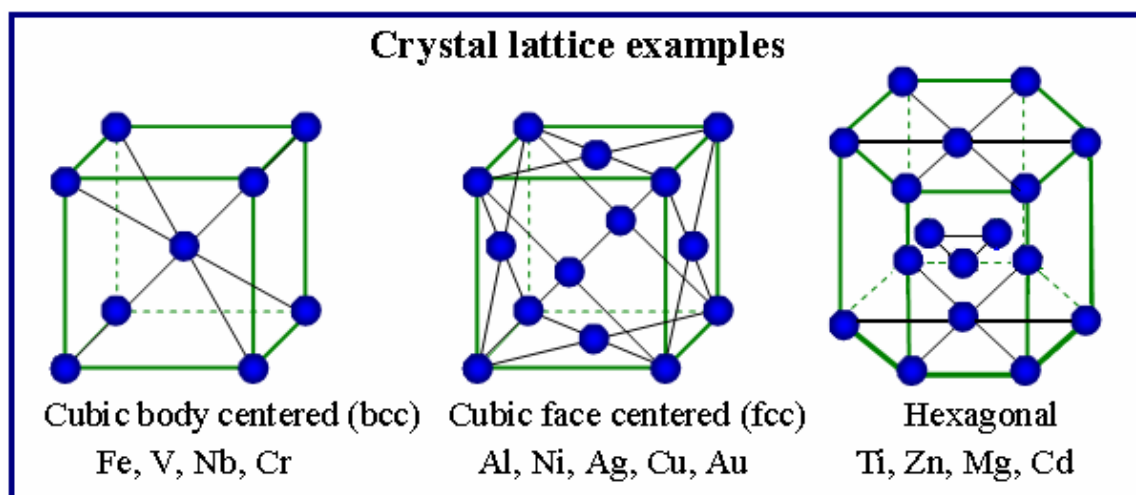
In this type of structure the unit cell (with cube shape) contains one atom at each of its 8 corners and another atom at the centre of the body . the common examples of this type of structure are *α -iron* (below 910 °C) , *δ - iron* (1400 °C to 1538 °C) , *tungsten* , *vanadium* , *molybdenum* , *chromium* , *alkali metals* (i.e. *sodium* , *cesium* ...etc.) as shown in{fig- 5}.

Face Centered Cubic Structure (FCC): b-

In this type of structure , the unit cell (in the shape of a cube) contains one atom at the centre of each face, in addition to one atom at each of its 8 corners as shown in{fig- 5} .The common examples of this type of structure are *γ -iron* (910°C to 1400 °C) , *copper* , *silver* , *gold* , *nickel* , *aluminum* , *lead* , *platinum* ... etc, the face centered cubic structures are also found in *ceramic crystals* .

Hexagonal Close Packed Structures (HCP) 2-

In this type of structure , the unit cell contains one atom at each corner of the hexagonal , one atom at centre of each faces of the hexagonal as shown in {fig- 5}and three atoms at the centre of the body. the common examples of this type of structure are *magnesium* , *Zinc* , *titanium* , *zirconium* , *cadmium* ,...etc .



Atomic Packing Factor (PF) :

The ratio of actual volume of atoms per unit cell to volume of the unit cell is known as **atomic packing factor** . the atomic packing factor for three types of cubic structures can be calculated as follow .

1-Simple Cubic Structure (SC):

Calculation the packing factor of (SC) crystal structure

$$PF \% = \frac{V_{atom} \times N_b}{V_{unit\ cell}} \times 100 \quad \text{----- (1)}$$

$$V_{atom} = \frac{4 \pi}{3} r^3 \quad \text{----- (2)}$$

$$N_b = N_b \text{ (of atoms positionned at the corners)} \quad \text{----- (3)}$$

$$N_b = \left(\frac{1}{8} \times 8 \right) = 1 \quad \text{----- (3)}$$

$$V_{unit\ cell} = a \times a \times a = a^3 \quad \text{----- (4)}$$

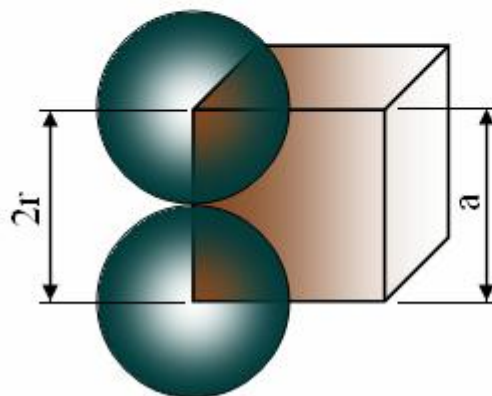
By substituting equations (2) , (3) and (4) in equation (1)

$$PF \% = \frac{\frac{4 \pi}{3} r^3 \times 1}{a^3} \times 100 \quad \text{----- (5)}$$

Inorder to solve the equation (5) we must find the relationship between a and r

$$a = 2r \quad \text{----- (6)} \quad \text{(from the fig. bellow)}$$

By substituting the eq. (6) in eq (5) and making some calculation the PF% will = 52%



2-Body Centered Cubic Structure(BCC):

Calculation the packing factor of (BCC) crystal structure

$$PF \% = \frac{V_{\text{atom}} \times N_b}{V_{\text{unit cell}}} \times 100 \quad \text{----- (1)}$$

$$V_{\text{atom}} = \frac{4 \pi}{3} r^3 \quad \text{----- (2)}$$

$$N_b = N_b \text{ (of atoms positioned at the corners) } + \quad \text{----- (3)}$$

$$N_b \text{ (of atoms positioned at the center of the body)}$$

$$N_b = \left(\frac{1}{8} \times 8 \right) + (1 \times 1) = 2 \quad \text{----- (3)}$$

$$V_{\text{unit cell}} = a \times a \times a = a^3 \quad \text{----- (4)}$$

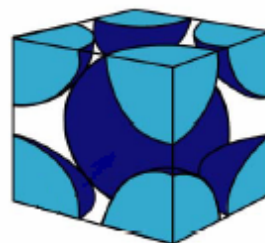
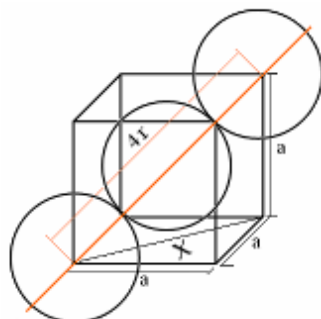
By substituting equations (2), (3) and (4) in equation (1) and making some abbreviations

$$PF \% = \frac{\frac{4 \pi}{3} r^3 \times 2}{a^3} \times 100 \quad \text{----- (5)}$$

In order to solve the equation (5) we must find the relationship between a and r

$$a = \frac{4r}{\sqrt{3}} \quad \text{----- (6) (from the fig.)}$$

By substituting the eq. (6) in eq. and making some calculation the PF% will = 68 %



3-Face Centered Cubic Structure (FCC):

Calculation the packing factor of (FCC) crystal structure

$$PF \% = \frac{V_{\text{atom}} \times N_b}{V_{\text{unit cell}}} \times 100 \quad \text{----- (1)}$$

$$V_{\text{atom}} = \frac{4 \pi}{3} r^3 \quad \text{----- (2)}$$

$$N_b = N_b (\text{ of atoms positioned at the corners }) + \quad \text{----- (3)}$$

$$N_b (\text{ of atoms positioned at the center of the faces })$$

$$N_b = \left(\frac{1}{8} \times 8 \right) + \left(6 \times \frac{1}{2} \right) = 4 \quad \text{----- (3)}$$

$$V_{\text{unit cell}} = a \times a \times a = a^3 \quad \text{----- (4)}$$

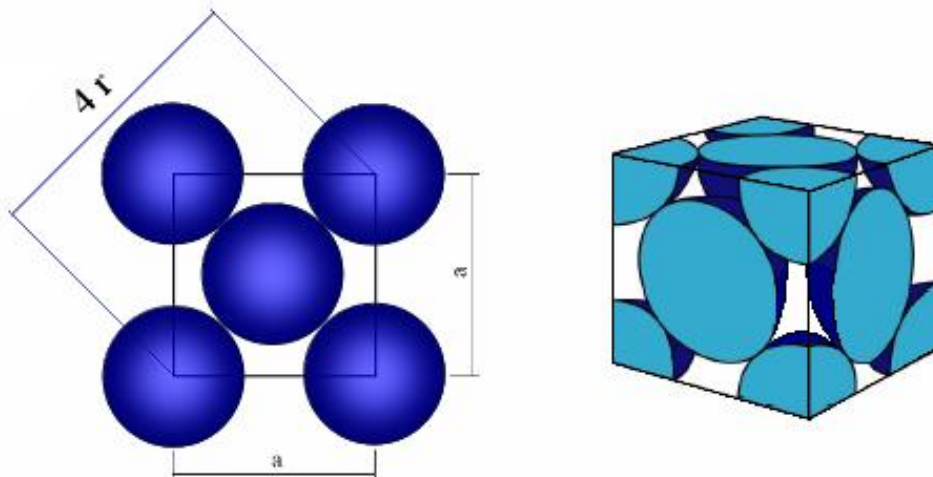
By substituting equations (2), (3) and (4) in equation (1)

$$PF \% = \frac{\frac{4 \pi}{3} r^3 \times 4}{a^3} \times 100 \quad \text{----- (5)}$$

In order to solve the equation (5) we must find the relationship between a and r

$$a = \frac{4}{\sqrt{2}} r \quad \text{----- (6)} \quad (\text{ from the fig. })$$

By substituting the eq. (6) in eq. and making some calculation the PF% will = 74 %



Atomic Bonds

There are two types of bonds; primary and secondary bonds .

Primary Bonds:

Primary bonds are the strongest bonds which hold atoms together. The three types of primary bonds are:

- 1- Metallic Bonds
- 2- Covalent Bonds
- 3- Ionic Bonds

1- Metallic Bonds :

In a metal, the outer electrons are shared among all the atoms in the solid. Each atom gives up its outer electrons and becomes slightly positively charged as shown in fig (1). The negatively charged electrons hold the metal atoms together. Since the electrons are free to move, they lead to good thermal and electrical conductivity.

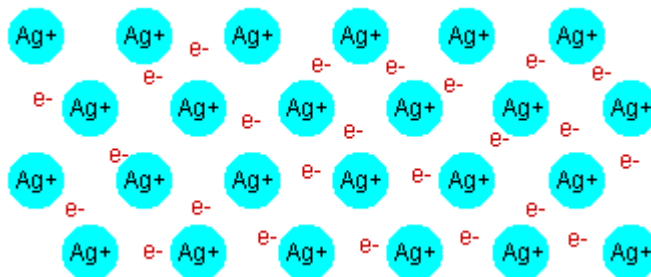


Figure 1. Metallic bond.

The lack of oppositely charged ions in the metallic structure and lack of sufficient valence electrons to form a true covalent bond necessitate the sharing of valence electrons by more than two atoms. Each of the atoms of the metal contributes its valence electrons to the formation of the negative "**electron cloud**". These electrons are not associated with a particular ion but are free to move among the positive metallic ions in definite energy levels. The metallic ions are held together by virtue of their mutual attraction for the negative electron cloud. This is illustrated schematically in Figure 2. The metallic bond may be thought of as an extension of the covalent bond to a large number of atoms.

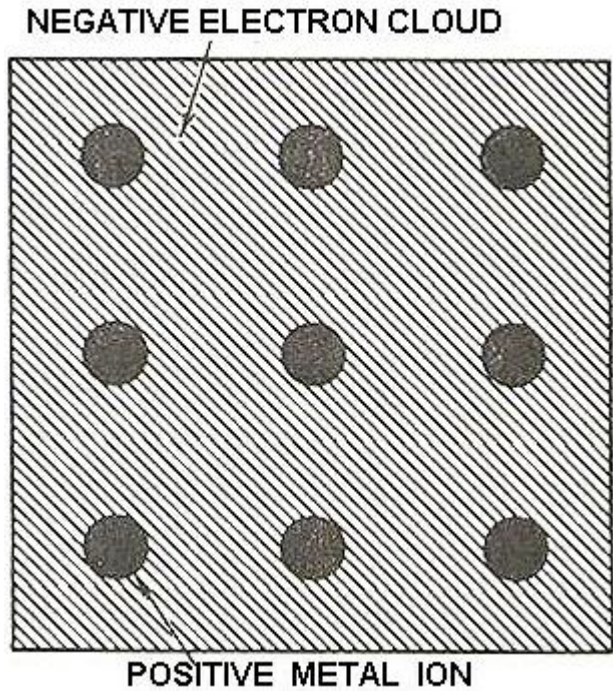


Figure 2. Metallic bond and electron cloud

2- Ionic Bonds :

Atoms like to have a filled outer shell of electrons. Sometimes, by transferring electrons from one atom to another, electron shells are filled. The **donor atom** will take a positive charge, and the **acceptor** will have a negative charge. The **charged atoms or ions** will be attracted to each other, and form bonds. The compound **NaCl**, or table salt, is the most common example.

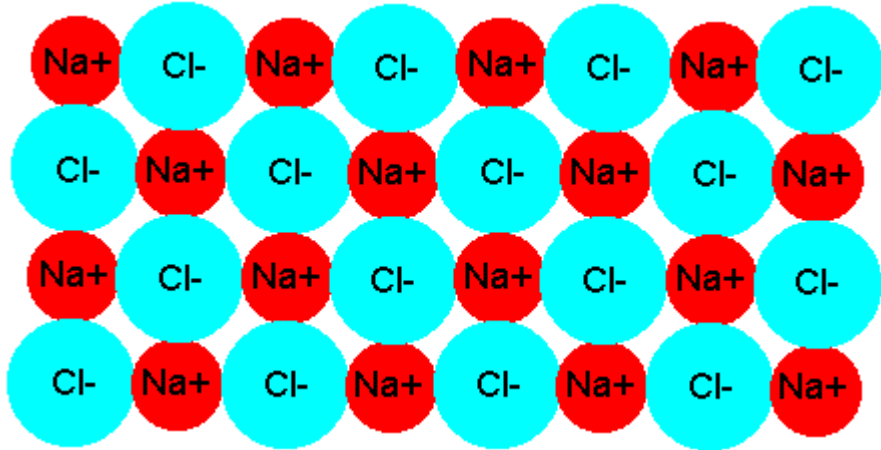


Figure 3. Ionic bond

The electron structure of atoms is relatively stable when the outer shells contain eight electrons (or two in the case of the first shell). An element

like sodium with one excess electron will give it up so that it has a completely filled outer shell. It will then have more protons than electrons and become a positive ion (charged atom) with a **+1** charge. An atom of chlorine, on the other hand, with seven electrons in its outer shell would like to accept one electron. When it does, it will have one more electron than protons and become a negative ion with a **-1** charge. When sodium and chlorine atoms are placed together, there will be a transfer of electrons from the sodium to the chlorine atoms, resulting in a strong electrostatic attraction between the positive sodium ions and the negative chlorine ions.

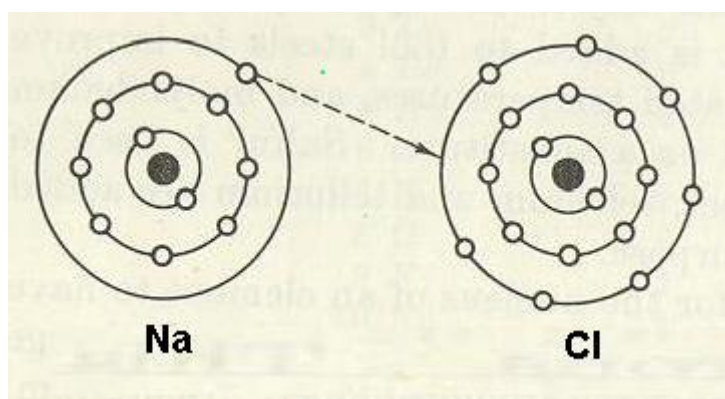


Figure 4a. Formation of ionic bond in NaCl.

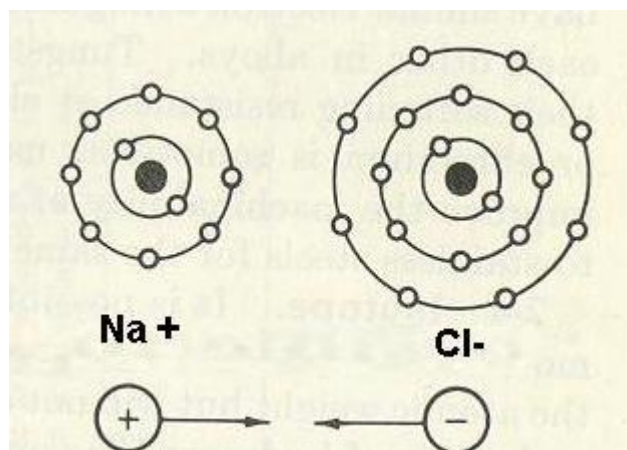


Figure 4b. Na⁺ and Cl⁻ ions formed by ionic bonding mechanism.

3- Covalent Bonds :

Some atoms like to share electrons to complete their outer shells. Each pair of shared atoms is called a covalent bond. Covalent bonds are called **directional** because the atoms tend to remain in fixed positions with respect to each other. Covalent bonds are also very strong. Examples include **diamond**, and the **O-O** and **N-N** bonds in oxygen and nitrogen gases.

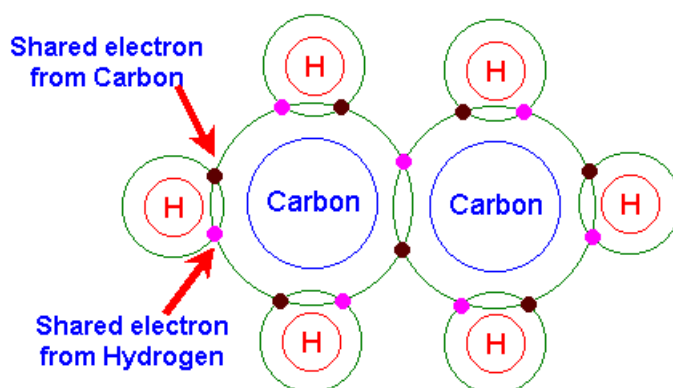


Figure 5. Covalent bonding.

Secondary Bonds:

Secondary bonds are much weaker than primary bonds. They often provide a "**weak link**" for deformation or fracture. Example for secondary bonds are:

- 1- Hydrogen Bonds
- 2- Vander Waals Bonds

1- Hydrogen Bonds :

Hydrogen bonds are common in covalently bonded molecules which contain hydrogen, such as water (**H₂O**). Since the bonds are primarily covalent, the electrons are shared between the hydrogen and oxygen atoms. However, the electrons tend to spend more time around the oxygen atom. This leads to a small positive charge around the hydrogen atoms, and a negative charge around the oxygen atom. When other molecules with this type of charge transfer are nearby, the negatively charged end of one molecule will be weakly attracted to the positively charged end of the other molecule. The attraction is weak because the charge transfer is small.

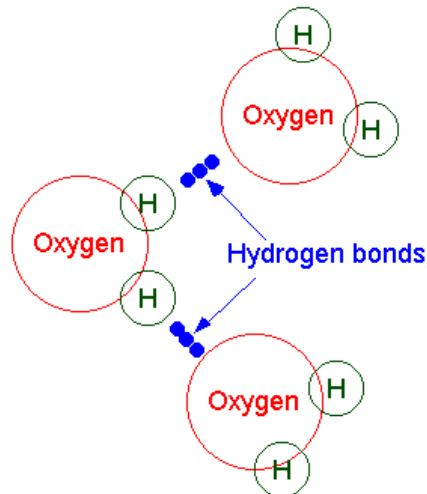


Figure 6. Hydrogen bonds.

2- Vander Waals Bonds :

Vander Waals bonds are very weak compared to other types of bonds. These bonds are especially important in **noble gases** which are cooled to very low temperatures. The electrons surrounding an atom are always moving. At any given point in time, the electrons may be slightly shifted to one side of an atom, giving that side a very small negative charge. This may cause an attraction to a slightly positively charged atom nearby, creating a very weak bond. Vander Waals bonding is a secondary bonding, which exists between virtually all atoms or molecules, but its presence may be **obscured** if any of the three primary bonding types is present. **Secondary bonding forces arise from atomic or molecular dipoles**. In essence, an electron dipole exists whenever there is some separation of positive and negative portions of an atom or molecule. When an electron cloud density occurs at one side of an atom or molecule during the electron flight about the nucleus, Vander Waals forces are generated. This creates a dipole wherein one side of the atom becomes electrically charged and the other side has deficiency of electrons and is considerably charged positive. The atom is distorted as shown in Figure 7.

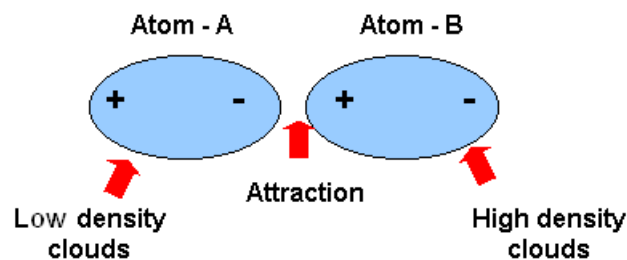


Figure 7. Vander Waals Bond

Table (1) : Explain a comparison between primary bonds

No.	Ionic bond	Covalent bond	Metallic bond
1-	It exists due to electrostatic force of attraction between positive and negative ions of different elements.	It exists due to the electrostatic force of attraction between atoms which share the electron pairs to form a covalent bond .	It exists due to electrostatic force of attraction between electron cloud and positive ions of same or different metals .
2-	It is formed between two different element . One of the atom loses its valence electron and the other accept it . The ions so formed .attract each other to form an ionic bond .	It is formed due to the sharing of electron pairs between the atoms of some or different elements .	It is formed when the valence electrons detach themselves from their parent atoms and form a common pool . The force which binds the electron cloud and the positive ions of the metal forms the metallic bond .
3-	The ionic solids have very low electrical and thermal conductivities .	The covalent solids have low electrical and thermal conductivities .	The metallic solids have high electrical and thermal conductivities .
4-	The ionic solids have high hardness due to their crystalline structure .	The covalent solids have low hardness except diamond silicon .	The metallic solids have crystalline structure but are soft .
5-	The ionic solids are not malleable and ductile .	The covalent solids are also not malleable and ductile .	The metallic solids are malleable and ductile .
6-	The ionic solids have high melting and boiling temperatures .	The covalent solids have lower melting and boiling temperatures than ionic solids .	The metallic solids have slightly lower melting and boiling temperatures than ionic solids .
7-	The ionic compounds exist in the form of solids only .	The covalent compounds exist in the form of solids , liquid and gases .	The metallic compounds also exist in the form of solids only .
8-	The ionic solids are soluble in water .	The covalent solids are soluble in benzene , toluene etc .	The metallic solids are neither soluble in water nor in benzene etc.

Crystallographic defect

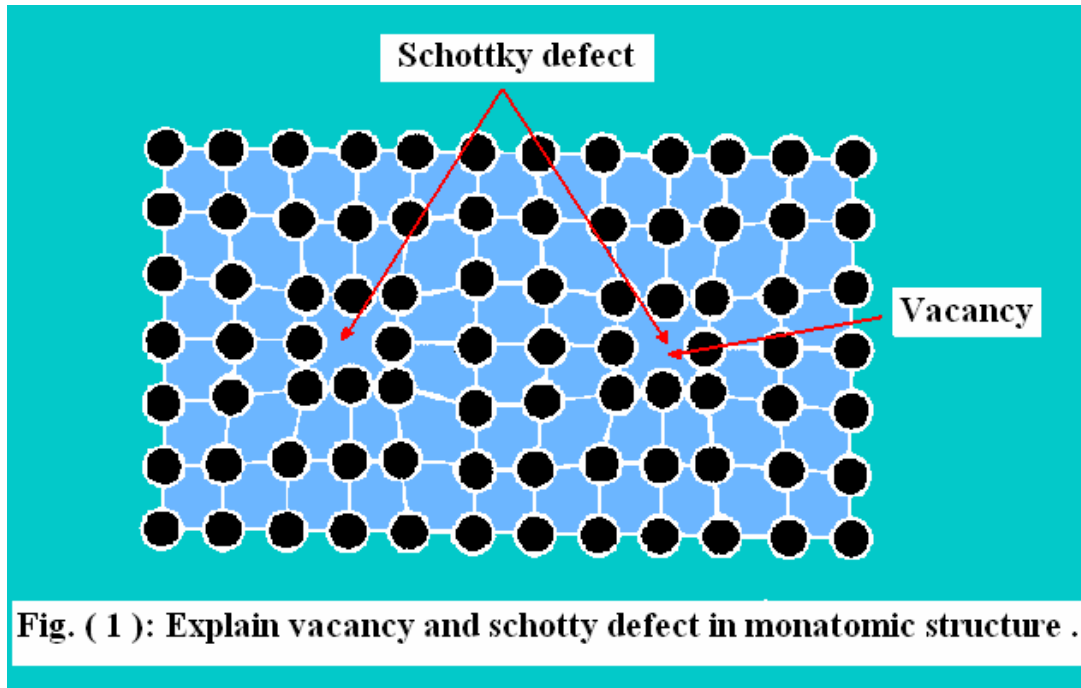
Crystalline solids have a very regular atomic structure: that is, the local positions of atoms with respect to each other are repeated at the atomic scale. These arrangements are called crystal structures, and their study is called crystallography. However, most crystalline materials are not perfect: the regular pattern of atomic arrangement is interrupted by crystal defects. The various types of defects are enumerated here.

1. Point defects
2. Line defects
3. Planar defects
4. Bulk defects

1 - Point defects :

Point defects are defects which are not extended in space in any dimension. There is not strict limit for how small a "point" defect should be, but typically the term is used to mean defects which involve at most a few extra or missing atoms without an ordered structure of the defective positions. For historical reasons, many point defects especially in ionic crystals are called "centers": for example the vacancy in many ionic solids is called an F-center.

- **Vacancies : are sites which are usually occupied by an atom but which are unoccupied** as shown in fig (1). If a neighboring atom moves to occupy the vacant site, the vacancy moves in the opposite direction to the site which used to be occupied by the moving atom. The stability of the surrounding crystal structure guarantees that the neighboring atoms will not simply collapse around the vacancy. In some materials, neighboring atoms actually move away from a vacancy, because they can better form bonds with atoms in the other directions. **A vacancy (or pair of vacancies in an ionic solid) is sometimes called a Schottky defect.**
- **Interstitials : are atoms which occupy a site in the crystal structure at which there is usually not an atom.** They are generally high energy configurations. Small atoms in some crystals can occupy interstices without high energy, such as hydrogen in palladium.



- A nearby pair of a vacancy and an interstitial is often called a **Frenkel defect** or **Frenkel pair** as illustrated in fig (2) .
- **Impurities** : occur because material are never 100% pure. In the case of an impurity, the atom is often incorporated at a regular atomic site in the crystal structure. This is neither a vacant site nor is the atom on an interstitial site and it is called a **substitutional defect** as shown in fig (2) .The atom is not supposed to be anywhere in the crystal, and is thus an impurity.
- **Anti-site defects** : occur in an ordered alloy. For example, some alloys have a regular structure in which every other atom is a different species, for illustration assume that type (**A**) atoms sit on the cube corners of a cubic lattice, and type (**B**) atoms sit in center of the cubes as illustrated in fig (3) . If one cube has an (**A**) atom at its center, the atom is on a site usually occupied by an atom, but it is not the correct type. This is neither a vacancy nor an interstitial, nor an impurity but it is anti – site defect.

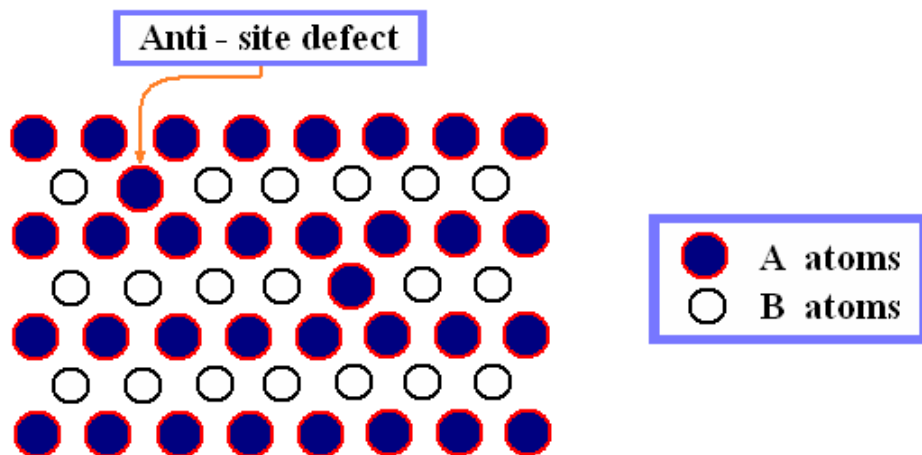
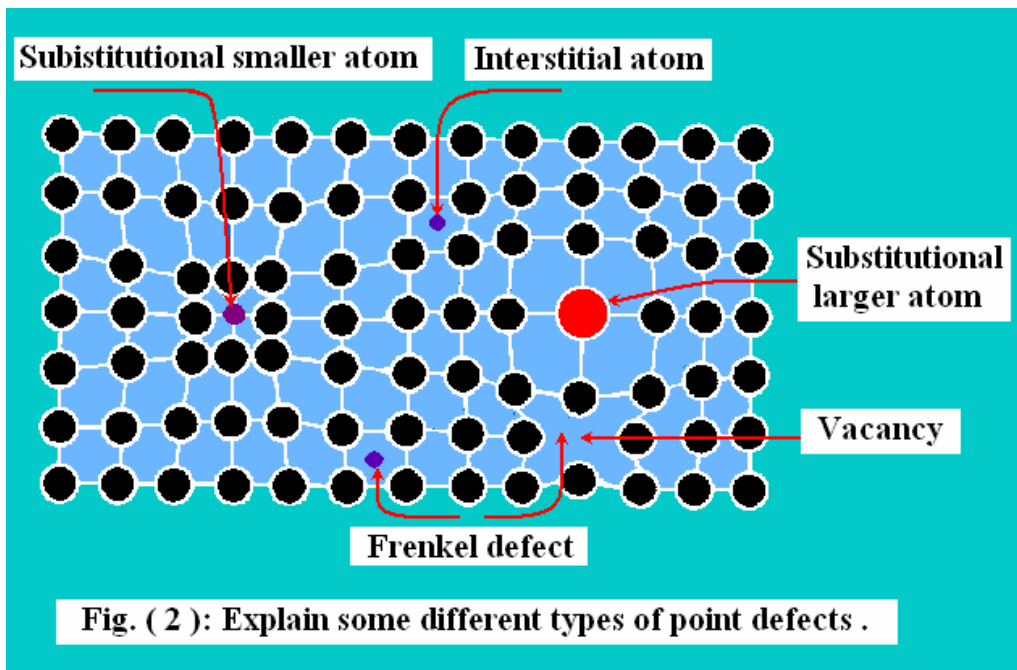


Fig. (3) : Explain Anti - site defect in ordered alloy .

2 - Line defects :

Line defects can be described by gauge theories.

- **Dislocations** are linear defects around which some of the atoms of the crystal lattice are misaligned. There are two basic types of dislocations, the EDGE dislocation and the SCREW dislocation. ("MIXED" dislocations combining aspects of both types are also common).

Edge dislocations are caused by the termination of a plane of atoms in the middle of a crystal as explained in fig (4). In such a case, the adjacent planes are not straight, but instead bend around the edge of the terminating plane so that the crystal structure is perfectly ordered on either side. The analogy with a stack of paper is apt: if a half a piece of paper is inserted in a stack of paper, the defect in the stack is only noticeable at the edge of the half sheet. The **screw dislocation** is more difficult to visualize, but basically comprises a structure in which a helical path is traced around the linear defect (dislocation line) by the atomic planes of atoms in the crystal lattice as shown in fig (5). The presence of dislocations results in lattice strain (distortion). The direction and magnitude of such distortion is expressed in terms of a **Burgers vector** (b). For an edge type, b is perpendicular to the dislocation line, whereas in the cases of the screw type it is parallel. Dislocations can be observed using **transmission electron microscopy**, **field ion microscopy** and **atom probe** techniques.

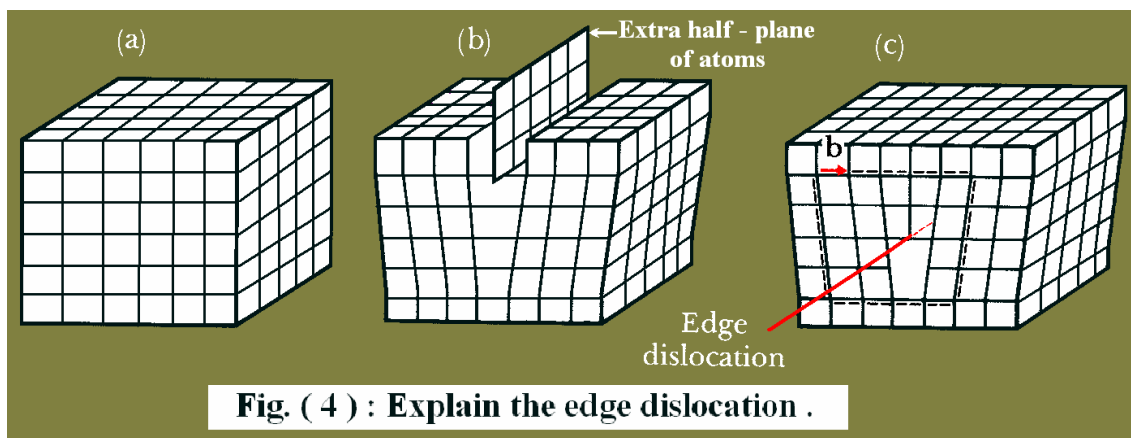


Fig. (4) : Explain the edge dislocation .

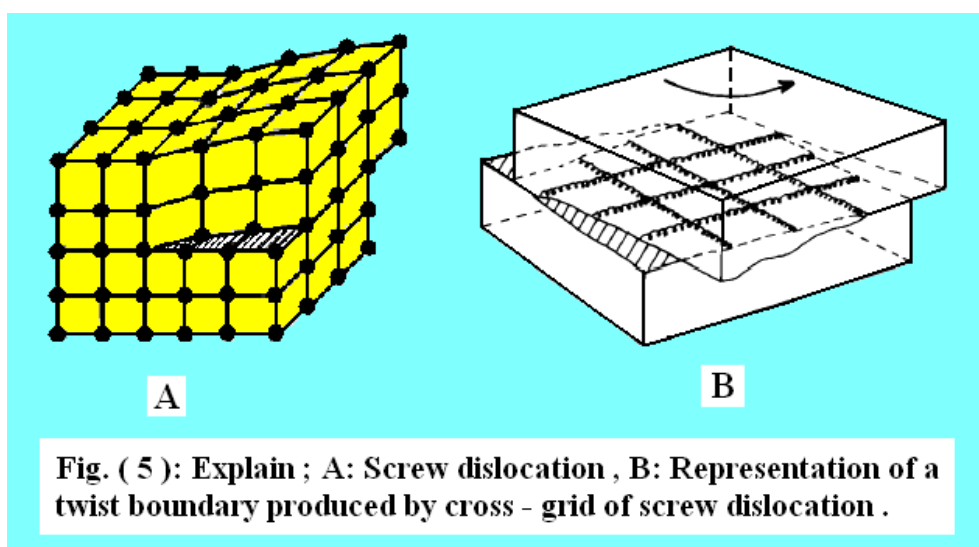


Fig. (5) : Explain ; A: Screw dislocation , B: Representation of a twist boundary produced by cross - grid of screw dislocation .

Planar defects :

- **Grain boundaries** occur where the crystallographic direction of the lattice abruptly changes. This commonly occurs when two crystals or more begin growing separately and then meet. Fig.(6) is clearly illustrate the grain boundary.

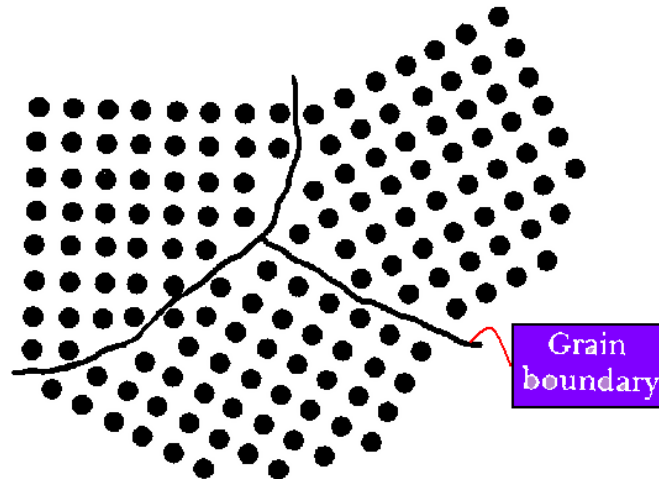
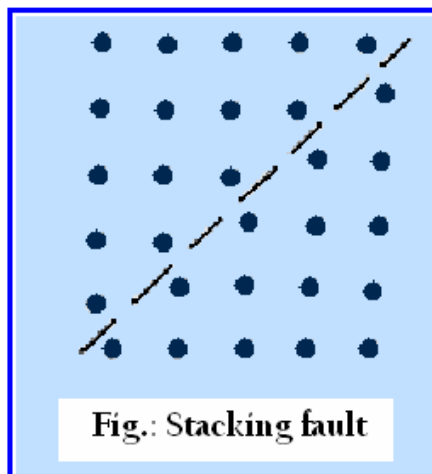


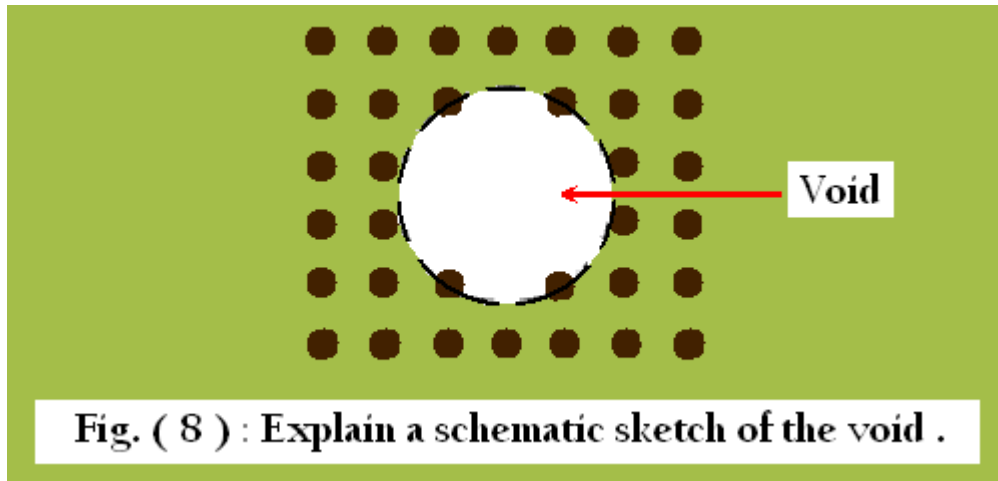
Fig. : Explain the grain boundary between different crystals (grains) .

- **Stacking faults** occur in a number of crystal structures, but the common example is in **close-packed** structures. **Face-centered cubic (fcc)** structures differ from **hexagonal close packed (hcp)** structures only in stacking order. A stacking fault is a one or two layer interruption in the stacking sequence. Fig (7) is a simple sketch illustrate the configuration of stacking fault .



Bulk defects (Volume defects) :

- **Voids** are small regions where there are no atoms as it is visualized in fig (8), and can be thought of as clusters of vacancies. Voids are formed in an intermediate temperature range 0.3 to $0.6T_m$.



- **Impurities** can cluster together to form small regions of a different phase. These are often called **precipitates**.

Solidification of Metals :

The atoms of a molten metal are in the state of random motion, occupying no fixed position. As the molten metal cools, the extent of the random motion of the atoms diminishes until at the freezing point, where atoms occupy fixed position with regard to one another resulting crystalline solid mass. **Crystallization** may begin at numerous places within the melt Fig.(1-A) The exact mechanism by which crystallization is initiated is not definitely known (because of the random motion of atoms, in the liquid metal and their closeness to each other). It can be assumed from time to time a small groups of atoms became arranged in the proper geometrical configuration to form the small amount of metal. When the solidification temperature is reached, collection that form into proper arrangement for crystallization are drawn together into stable groups by the binding forces between the atoms. They become solid and provide **seeds** for further solidification, each called **nucleus** or "**centre**" of crystallization as illustrated in fig.(1-A) , by continuing the solidification process the former formed nucleus will grow to small crystals shown in fig. (1-B) . This step is carried out by the addition of new atoms to them . The growth of the small crystals will tends later to a visible proportions in what is called a "**dendrite crystals**" as shown in fig. (1-C) . Finally the solidification process will stop by formation of the crystal (grain boundary) between the crystals due to the stacking fault .Those formed crystal either gives no hint to the impurities between the dendritic arms ; as visualized in fig. (1-D) , or the impurities are carried between their dendritic arms as visualized in fig. (1-E) .

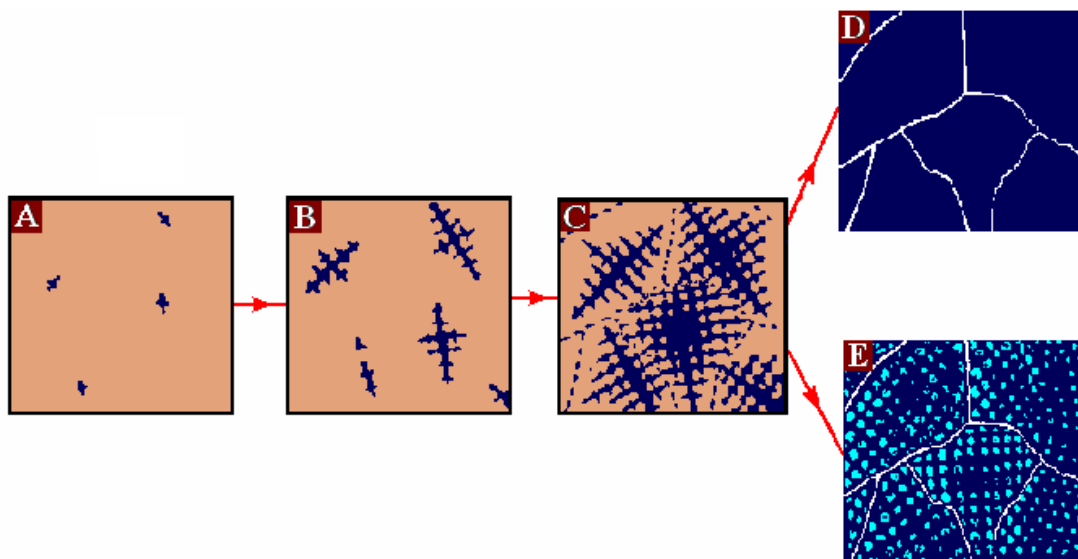
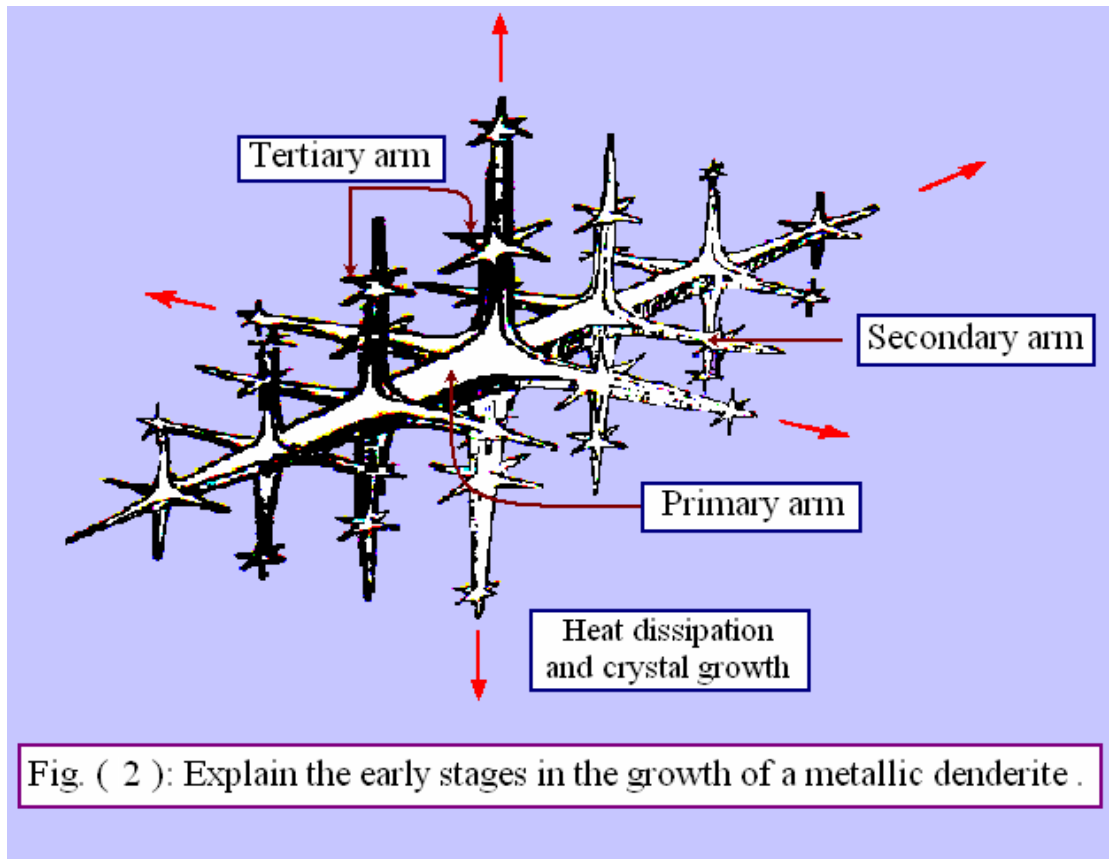


Fig (1): Explain the steps of dendritic growth ; A: Nucleus formation ; B: Crystals formation ; C: Crystals growth and crystal (grain) boundary formation ; D: The crystalline gives no hint to their dendritic origin since all atoms are identical ,but an impure metal ; E: crystals are carried the impurities between the dendritic arms , thus revealing the metal skeleton .

The **dendrite crystal** is a sort of crystal skeleton, from which the secondary arms begin to grow (starting from different positions on the primary arm) in other directions depending upon the lattice pattern. From these secondary arms, tertiary arms begin to grow. The configuration of dendrite crystal is well explained in fig. (2) .

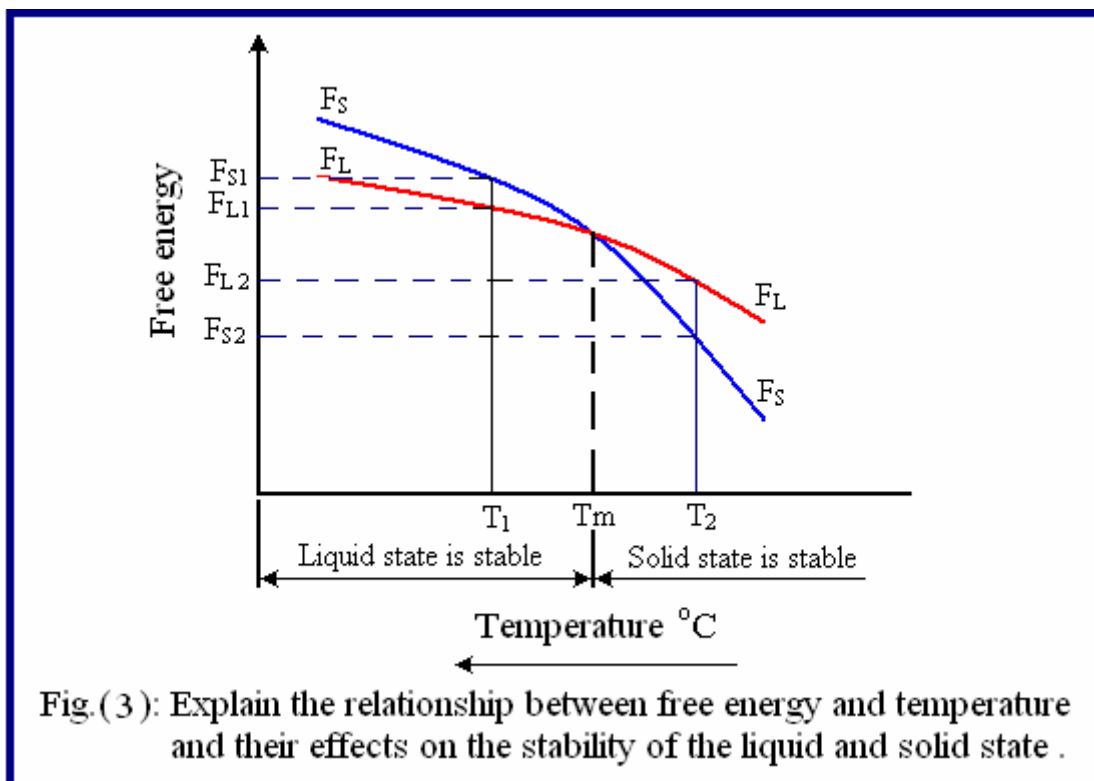


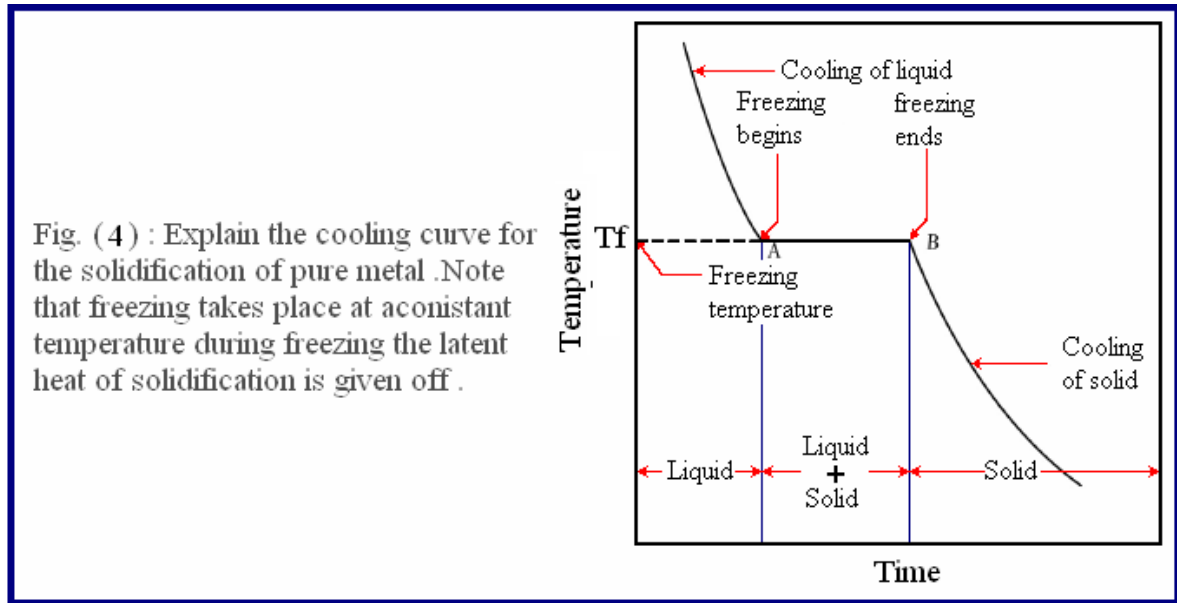
The crystallization occurs when metal state change to a more stable state in a point view of thermodynamics. That is the solid state possesses a less free energy than the melt . Fig. (3) below shows change of free energy for melt metal F_L and solid F_S with temperature. At T_m (melting temperature) the two energies equalize, so T_m is corresponding to the crystallization equilibrium temperature at which the two phases can be found simultaneously. At ($T_1 > T_m$) the liquid be more stable because its free energy be less and vice versa. Crystallization remain continuous if there is a difference in free energy (ΔF), that is the free energy for solid metal F_S is less than that of melt (liquid) F_L . See fig (3) .

Cooling curve of pure metal:

Suppose that a piece of pure metal is heated by an electric furnace to temperature above its melting temperature (T_m) , the solid metal will become molten (liquid) . Hence if the furnace is turned off a decrease in the temperature of the molten metal will take place to a definite

temperature denoted by letter (**A**) in the fig. (4) . This decrease in the temperature can be revealed by using a suitable thermometer (provided with appropriate thermocouple contacting with its end the surface of the molten metal) . The metal at this range of temperatures will be at liquid state . For an interval (started from point **A** and ended at **B**) the recorded temperature by thermometer will become definite number .This number is denote to the freezing temperature (**T_f**)of the metal ; which is in turn equal to the melting temperature (**T_m**) for pure metal . The stability of the temperature at (**T_f**) is known as **thermal arrestment** .At this thermal arrestment both liquid and solid states are presented together with continuous increase in the amount of the solid fraction by moving toward the point (**B**) . By continuing the cooling process and just bellow the freezing temperature (**T_f**) the thermometer return to detect a continuous decrease in the temperature until reaching to the room temperature . At the final range of temperature the metal will be at solid state . The former description of the cooling process is well illustrated in fig. (4) .





From fig. (5); one can conclude that the crystallization actually occurs only when metal cooled below T_m . The difference between T_m and T_c (T_1 , T_2 , T_3 , T_4 & T_5), at which crystallization occurs, is called **the temperature of under cooling (ΔT)** .

$$\Delta T = T_m - T_c$$

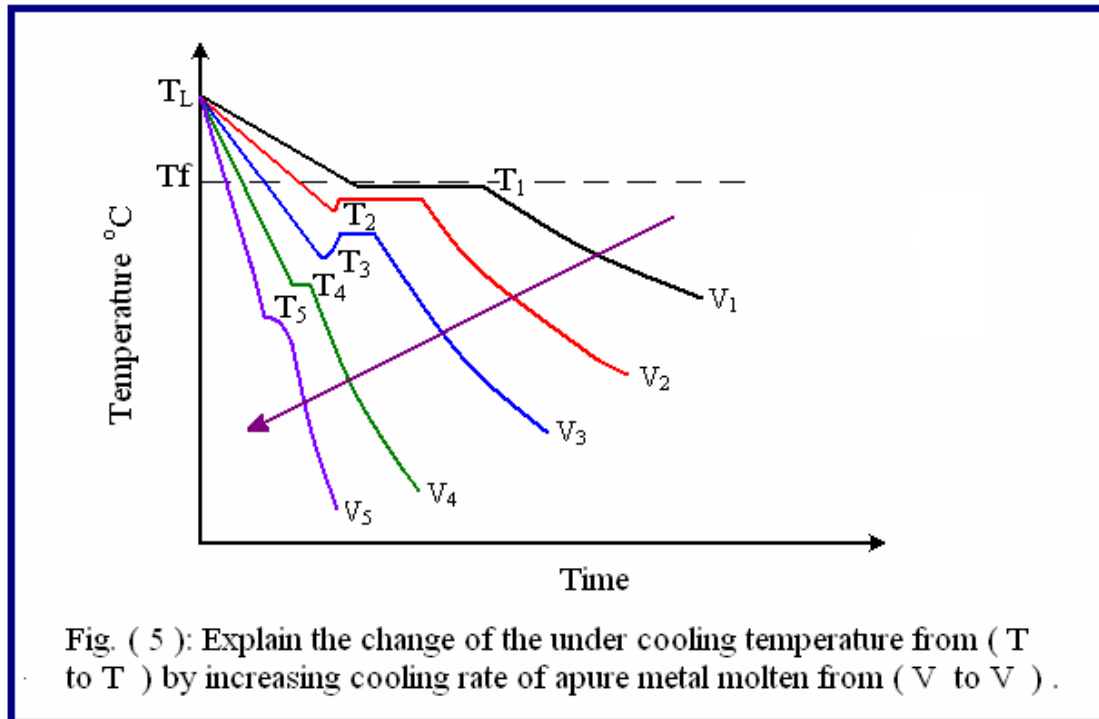
Also fig. (5) represents cooling curves for crystallization a pure metal under different **cooling rates (V)**. In the case of very slow cooling rate the temperature of under cooling ΔT , is small, that means crystallization occurs at a temperature near below the equilibrium temperature T_m (**curve V_1**). Horizontal lines appear in the cooling curves of metals at crystallization temperature (no temperature gradient) due to latent heat at the freezing point. As cooling rates are increased , the under cooling temperature also increases (**curves V_2 , V_3 , V_4 & V_5**), so freezing occurs at temperatures much less than (T_m) .The value of (ΔT) depends on the nature and purity of metal usually :

$$\Delta T \approx 10^\circ\text{C} - 30^\circ\text{C}$$

Grain Size:

As mentioned before, that crystallization occurs at numerous places called "**nuclei of crystallization**" or some times called "**embryo**". The rate at which a molten metal is cooling when it reaches its freezing point affects the size of crystals which form. A slow fall in temperature, will leads to the formation of relatively few embryos, so that the resultant crystals (grains) will be large (they may be seen without microscope).

Rapid cooling leads to the formation of a large number of nuclei of small size, as the cooling rate increases the nuclei formation be faster than crystal formation which leads to minimize the grain size in the frozen metal.



Other factors that increase the rate of nucleation, thus promoting the formation of fine grain, are:-

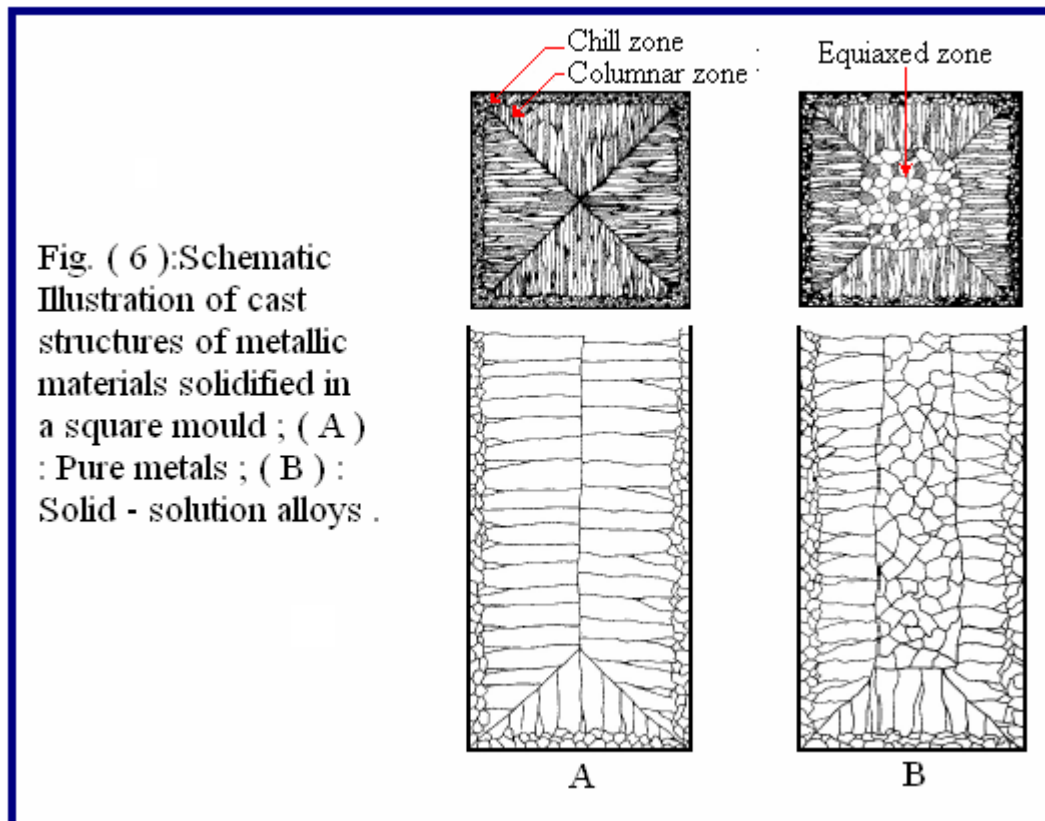
- (1) **Insoluble impurities** such as aluminum and titanium that form insoluble oxides in steel.
- (2) **Stirring** the melt during solidification which tends to break up the crystals before they have a chance to grow very large.

In general, fine-grained material exhibit better toughness or resistance to shock, they are harder and stronger than coarse-grained materials.

Metallic ingots structures:

The grain size structure of the metallic **ingots**, may vary considerably from outside surface to the center fig (6). This is due to the variation which exists in the temperature gradient as the ingot solidifies and heat is transmitted from the metal to the mould . small grains form at the surface of ingot. As the mould warms up the formation of nuclei will be related as solidification proceeds. Thus grains which grow towards the center of the ingot will be larger. In an intermediate position the rate of cooling is favorable to the formation of elongated columns grains. If the mould has sharp edges, a plane of weakness will develop from this corner because

soluble gases and solid impurities tend to concentrate along this plane. Fig. (6) show the difference between the structure of a metallic ingot and other one belongs to an alloy . Where the structure of the later one is consisted from three zones (**chill , columnar & equiaxed zone**) ; while the structure of the pure metallic ingot is formed only from two zones .The reason for this difference is belongs to the yielding of the alloy ingot to structural effect beside heat effect ;while a pure metallic ingot is affected only by heat effect .



Castings Defects:

A number of defects can occurs within the cast structures, such as, shrinkage cavities, porosity (blowholes), and segregation of impurities.

(1) Shrinkage cavities:

The crystallized structure of most metals of engineering importance, represent a close packing of atoms. Liquid metal, with few exceptions, undergo a contraction in volume due to solidification. This decrease of volume may be as much as **6%**. In a properly designed mould provide liquid to the portion of metal that solidifies last will contract. If the external surface of the casting solidify first, the decrease in volume of the interior during solidification will result in a large shrinkage cavity at the

mid section of the upper portion of the ingot . In the solidification of steel ingots, the shrinkage cavity, called **pipe**, which is usually presented at the top central portion of the ingot fig.(7-A) . This portion is cut off and discarded before working . If the bottom portion of the mould is designed to be wider than upper portion ; thus, the formation of secondary pipe at the lower portion of the mould as shown in fig. (7-B) will take place . The ideal solidification occurs when the metal first freeze at the bottom of the mould and continues up word to a riser at the top. If the casting does have heavy section a riser at the top should be supplied to supply the required liquid metal during solidification .

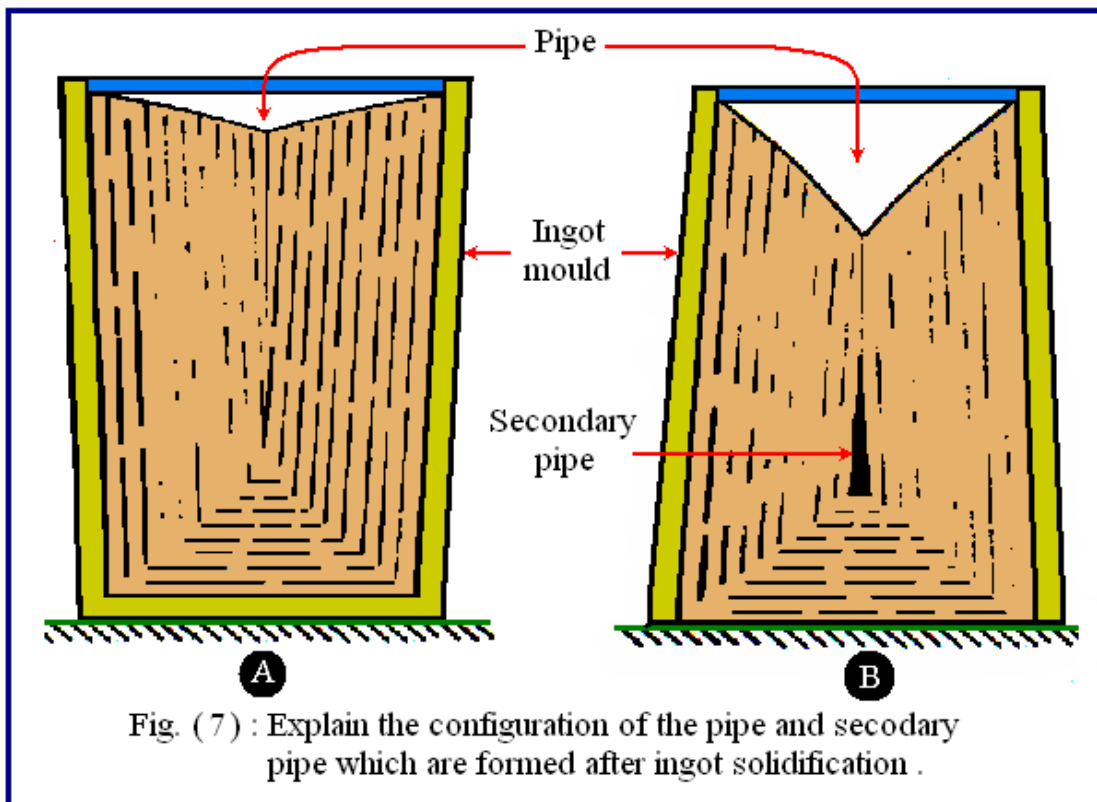


Fig. (7) : Explain the configuration of the pipe and secondary pipe which are formed after ingot solidification .

(2)Hot Tears:

Are the cracks formed due to heavy shrinkage strains set up in the solid casting just after solidification. A common cause is the failure of the sand mould due to collapse and allow the casting to contract. Hot tear, may also result from the non-uniform cooling conditions as in shrinkage. Fig. (8) explain the configuration of hot tears and the positions of their formation .

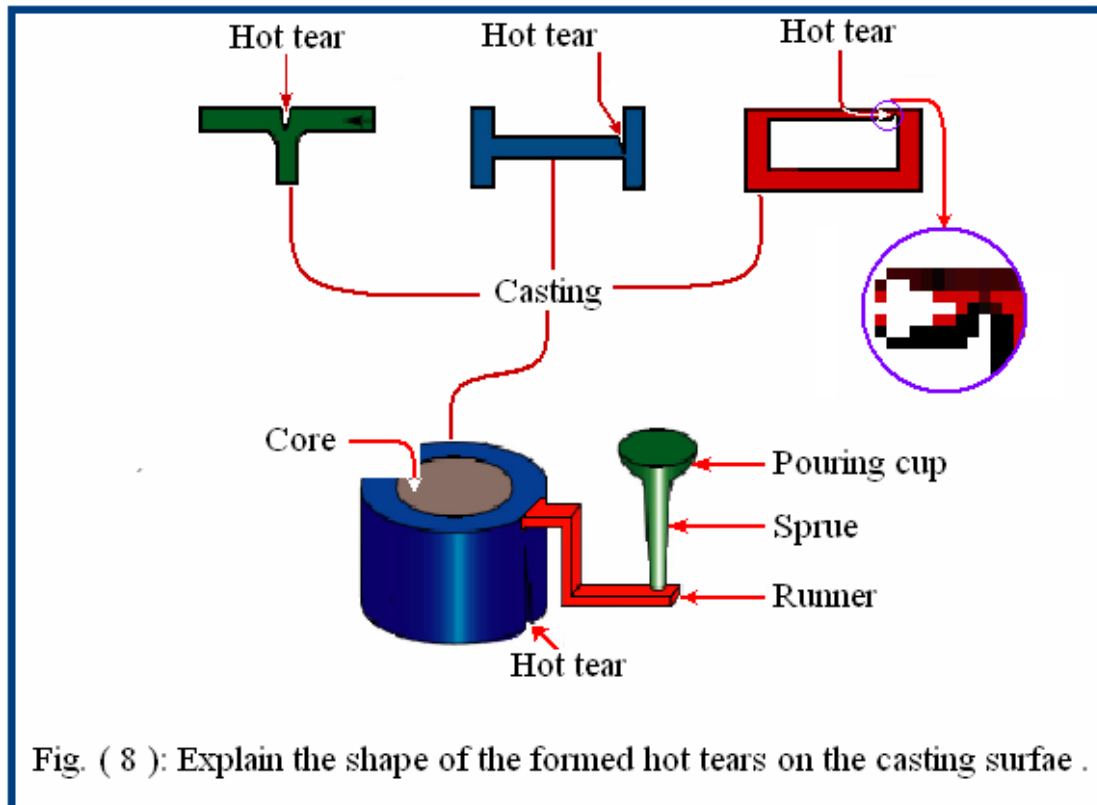


Fig. (8) : Explain the shape of the formed hot tears on the casting surfae .

(3)Porosity:

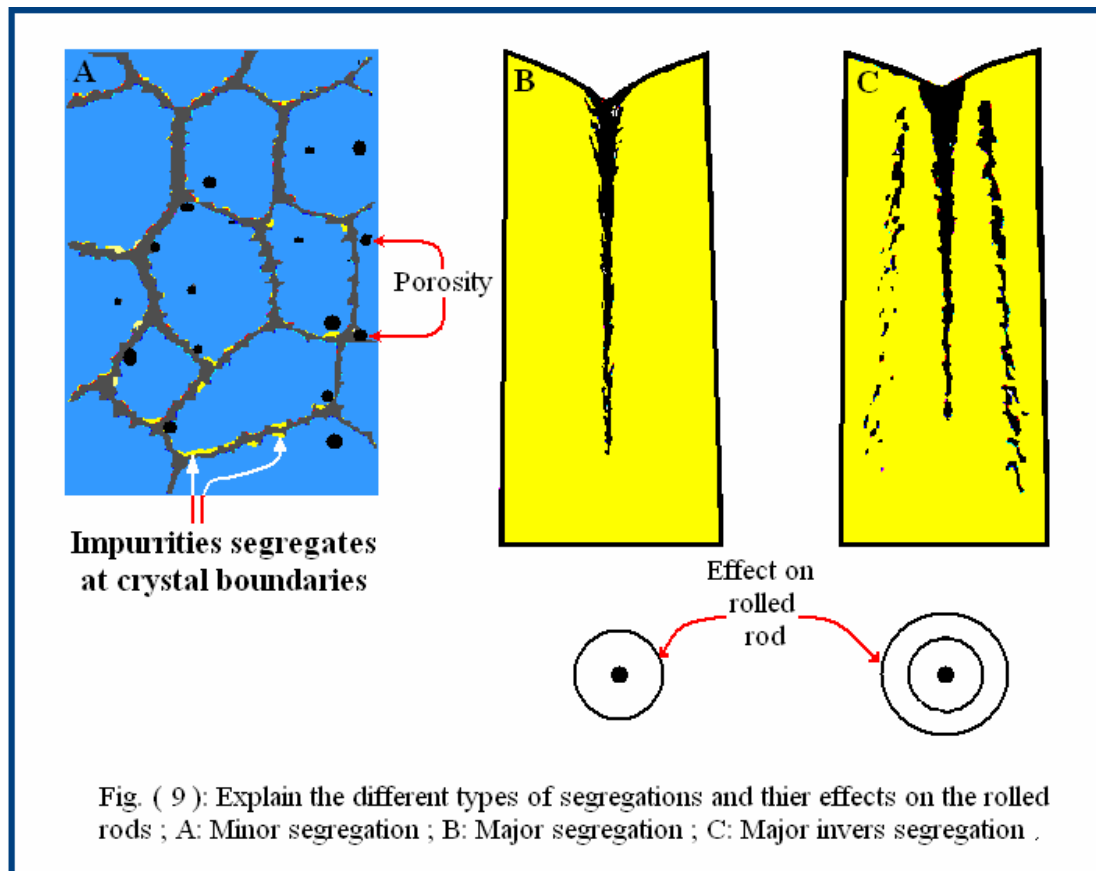
Porosity or **blowholes** explained in fig.(9-A) occur whenever gases are in the casting. They are usually more numerous and smaller than shrinkage cavities and may be distinguished by their rounded form. **Air** may be entrapped in the casting by the sudden rush of metal pouring. **Gases** may also be produced by reaction of the liquid metal with volatile substances , such as **moisture** in the metal. Porosity may be greatly reduced by proper venting of the mould and by not compacting the sand strongly .

(4)Segregation of Impurities:

There is a tendency for dissolved impurities to remain in that portion of the metal which solidifies at last. The dendrites which form first are of almost pure metal, so the imparities solidifies at last, thus the bulk of impurities contained at the grain boundaries, this is called **minor segregation** fig. (9-A) .

In other hand as grains begin to grow in words , they will push impurities towards center of ingot , causing a central pipe taking the shape of up word **V**. this is called **major segregation fig.** (9-B) .

From these types of segregation, minor segregation has more bad effect . It will cause overall brittleness of the casting and, make the ingot crumble during hot or cold-working processes.



From the forging remarks it be evident that a casting suffering from many different types of defect. Some defects can be detected by non-destructed inspections, but other defects may be detected only during service. Such difficulties are overcome by applying some mechanical working processes, (splitting, trimming , ...).

The use of another mechanical processes which tend to produce a product of greater uniformity in structure, mechanical properties may solve these problem . Forging is likely to be more reliable in service casting. Sometimes such factors as complicated help cost of production dictate the choice of casting .

Material Hardness

Definition of hardness :

Hardness may be defined as " **the resistance of metal to plastic deformation, usually by indentation** ". However, the term may also refer to **stiffness, or to resistance to scratching, abrasion, or cutting**. The greater the hardness of the metal, the greater resistance it has to deformation. In **mineralogy** the property of matter commonly described as the resistance of a substance to being scratched by another substance. In **metallurgy** hardness is defined as the ability of a material to resist plastic deformation. The resistance of a material to indentation is the usual type of hardness test, in which a pointed or rounded indenter is pressed into a surface under a substantially static load.

Hardness measurement :

Hardness measurement can be defined as **macro-, micro- or nano-scale** according to the forces applied and displacements obtained. Measurement of the macro-hardness of materials is a quick and simple method of obtaining mechanical property data for the bulk material from a small sample. It is also widely used for the quality control of surface treatments processes. However, when concerned with coatings and surface properties of importance to friction and wear processes for instance, the **macro-indentation** depth would be too large relative to the surface-scale features. Where materials have a fine microstructure, are multi-phase, non-homogeneous or prone to cracking, **macro-hardness** measurements will be highly variable and will not identify individual surface features. It is here that **micro-hardness** measurements are appropriate. Micro-hardness is the hardness of a material as determined by forcing an indenter such as a Vickers or Knoop indenter into the surface of the material under 15 to 1000 gf load; usually, the indentations are so small that they must be measured with a microscope. Capable of determining hardness of different microconstituents within a structure, or measuring steep hardness gradients such as those encountered in casehardening. Conversions from **micro-hardness** values to tensile strength and other hardness scales (e.g. Rockwell) are available for many metals and alloys. Micro-indenters works by pressing a tip into a sample and continuously measuring: applied load, penetration depth and cycle time. **Nano-indentation** tests measure hardness by indenting using very small, on the order of 1 nano-Newton, indentation forces and measuring the depth of the indentation that was made. These tests are based on new technology that allows precise measurement and control of the indenting

forces and precise measurement of the indentation depths. By measuring the depth of the indentation, progressive levels of forcing are measurable on the same piece. This allows the tester

1- To determine the maximum indentation load that is possible before the hardness is compromised and the film is no longer within the testing ranges.

2- Also allows a check to be completed to determine if the hardness remains constant even after an indentation has been made.

Hardness measurement methods:

There are three types of tests used with accuracy by the metals industry; they are the **Brinell hardness test**, the **Rockwell hardness test**, and the **Vickers hardness test**. Since the definitions of metallurgic ultimate strength and hardness are rather similar, it can generally be assumed that a strong metal is also a hard metal. Rockwell hardness test

Rockwell hardness test :

The Rockwell Hardness test is a hardness measurement based on the net increase in depth of impression as a load is applied. Hardness numbers have no units and are commonly given in the R, L, M, E and K scales. The higher the number in each of the scales means the harder the material. In the Rockwell method of hardness testing, the depth of penetration of an indenter under certain arbitrary test conditions is determined. The **indenter** may either be a **steel ball** of some specified diameter or a spherical **diamond-tipped cone of 120° angle and 0.2 mm tip radius**, called **Brale**. The type of indenter and the test load determine the **hardness scale(A, B, C, etc)**. A **minor load of 10 kg** is first applied, which causes an initial penetration and holds the indenter in place. Then , the dial is set to zero and the **major load** is applied. Upon removal of the major load, the depth reading is taken while the minor load is still on. The hardness number may then be read directly from the scale which is denotes to the difference in the depth of the indentation between the minor and major loads and provides the **Rockwell hardness number**. The hardness of **ceramic substrates** can be determined by the Rockwell hardness test, according to the specifications of **ASTM E-18**. Using standard hardness conversion tables, the Rockwell hardness value is determined for the load applied, the diameter of the indenter, and the indentation depth. The hardness testing of **plastics** is most commonly measured by the Rockwell hardness test . Rockwell hardness is generally

chosen for **'harder' plastics** such as nylon, polycarbonate, polystyrene, and acetal . With the Rockwell tester, the hardness is indicated directly on the scale attached to the machine. This dial like scale is really a depth gauge, graduated in special units. The Rockwell hardness test is the most used and versatile of the hardness tests. For **soft materials** such as copper alloys, soft steel, and aluminum alloys a 1/16" diameter steel ball is used with a 100-kilogram load and the hardness is read on the **"B" scale**. In testing **harder materials**, hard cast iron and many steel alloys, a 120 degrees diamond cone is used with up to a 150 kilogram load and the hardness is read on the **"C" scale**.. A properly used Rockwell designation will have the hardness number followed by **"HR"** (Hardness Rockwell), which will be followed by another letter which indicates the specific Rockwell scale. An example is **60 HRB**, which indicates that the specimen has a hardness reading of 60 on the B scale. There is a second Rockwell tester referred to as the **"Rockwell Superficial Hardness Tester"**. This machine works the same as the standard Rockwell tester, but is used to test thin strip, or lightly carburized surfaces, small parts or parts that might collapse under the conditions of the regular test. The Superficial tester uses a reduced minor load, just **3 kilograms**, and has the major load reduced to either **15 or 45 kilograms** depending on the indenter, which are the same ones used for the common scales. Using the **1/16"** diameter, steel ball indenter, a **"T"** is added (meaning thin sheet testing) to the superficial hardness designation. An example of a superficial Rockwell hardness is **15T-22**, which indicates the superficial hardness as 22, with a load of 15 kilograms using the steel ball. If the **120 °diamond cone** were used instead, the **"T"** would be replaced with **"N"**.

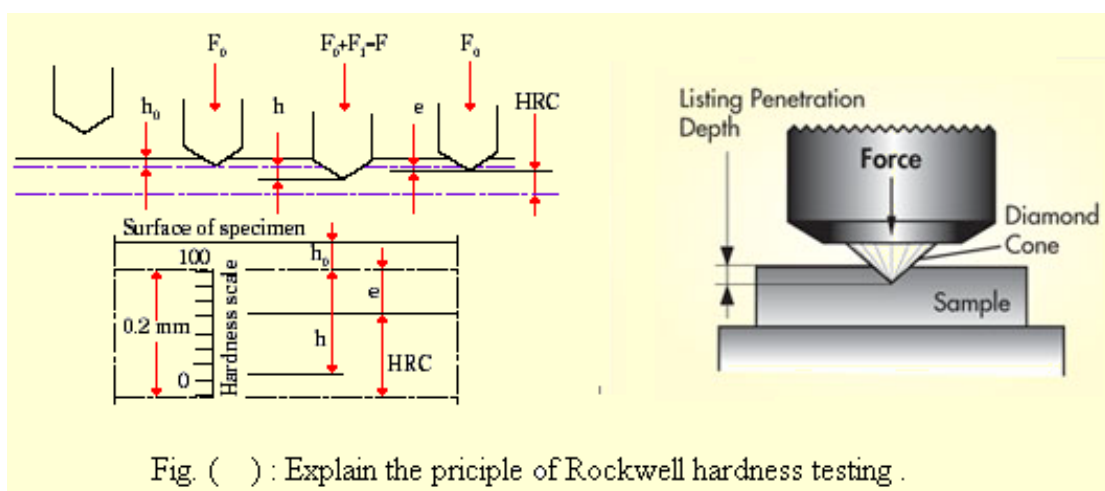
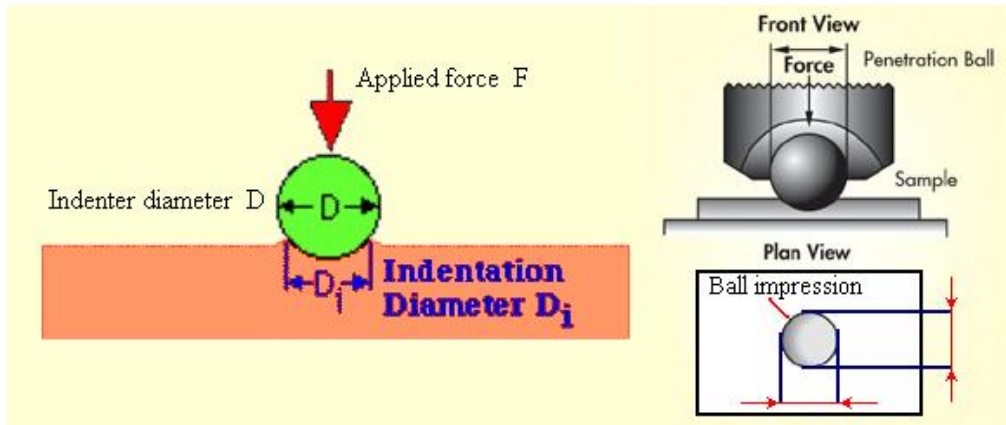


Fig. () : Explain the principle of Rockwell hardness testing .

Brinell hardness test :

Brinell hardness is determined by forcing a hard steel or carbide sphere of a specified diameter under a specified load into the surface of a material and measuring the diameter of the indentation left after the test. The Brinell hardness number, or simply the Brinell number, is obtained by dividing the load used, in kilograms, by the actual surface area of the indentation, in square millimeters. The result is a pressure measurement, but the units are rarely stated. The Brinell hardness test uses a desk top machine to press a 10mm diameter, hardened steel ball into the surface of the test specimen. The machine applies a load of 500 kilograms for soft metals such as copper, brass and thin stock. A 1500 kilogram load is used for aluminum castings, and a 3000 kilogram load is used for materials such as iron and steel. The load is usually applied for 10 to 15 seconds. After the impression is made, a measurement of the diameter of the resulting round impression is taken. It is measured to plus or minus .05mm using a low-magnification portable microscope. The hardness is calculated by dividing the load by the area of the curved surface of the indentation, (the area of a hemispherical surface is arrived at by multiplying the square of the diameter by 3.14159 and then dividing by 2). To make it easier, a calibrated chart is provided, so with the diameter of the indentation the corresponding hardness number can be referenced. A well structured Brinell hardness number reveals the test conditions, and looks like this, "**75 HB 10/500/30**" which means that a Brinell Hardness of 75 was obtained using a 10mm diameter hardened steel with a 500 kilogram load applied for a period of 30 seconds. On tests of extremely hard metals a tungsten carbide ball is substituted for the steel ball. The Brinell ball makes the deepest and widest indentation, so the test averages the hardness over a wider amount of material, which will more accurately account for multiple grain structures, and any irregularities in the uniformity of the alloy. The Brinell hardness test was one of the most widely used hardness tests during World War II. The **BHN** is calculated according to the following formula:



$$\text{BHN} = \frac{F}{\frac{\pi}{2} D \cdot (D - \sqrt{D^2 - D_i^2})}$$

where

BHN = the Brinell hardness number

F = the imposed load in kg

D = the diameter of the spherical indenter in mm

Di = diameter of the resulting indenter impression in mm

Several BHN tests are usually carried out over an area of armour plate. On a typical plate each test would result in a slightly different number. This is due not only to minor variations in quality of the armour plate (even homogenous armour is not absolutely uniform) but also because the test relies on careful measurement of the diameter of the depression. Small errors in this measurement will lead to small variations in **BHN** values. As a result, **BHN** is usually quoted as a range of values (e.g. **210 to 245**, or **210-245**) rather than as a single value. The BHN of face hardened armour uses a back slash '?' to separate the value of the face hardened surface from the value of the rear face. For example, a **BHN of 555\353-382** indicates the surface has a hardness of 555 and the rear face has a hardness of 353 to 382. The Brinell Hardness Test described above is called 'HB 10/3000 WC' and was the type of test used by the Germans in World War II. Other types of hardness tests use different materials for the sphere and/or different loads. Softer materials deform at high BHN which is why tungsten carbide (a very hard material) is used to measure armour plate. Even so, as the BHN goes above 650 the tungsten carbide ball begins to flatten out and the BHN values indicate a greater difference in hardness than there actually is, while above 739 the ball flattens out so badly that it cannot be used.

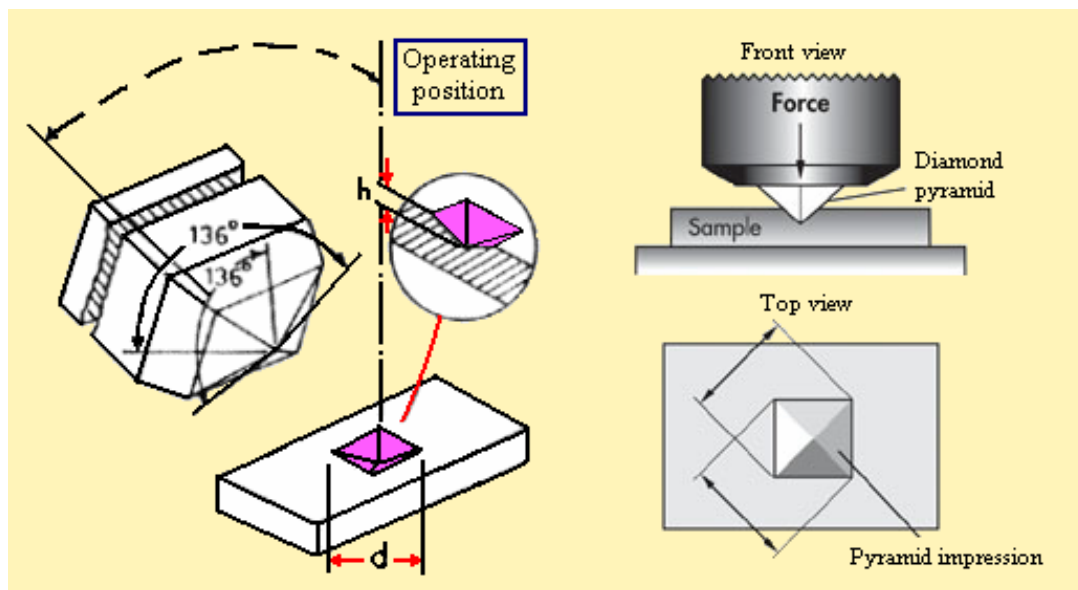
Vickers hardness test :

It is the standard method for measuring the hardness of metals, particularly those with extremely hard surfaces: the surface is subjected to a standard pressure for a standard length of time by means of a pyramid-shaped diamond. The diagonal of the resulting indentation is measured under a microscope and the Vickers Hardness value read from a conversion table . Vickers hardness is a measure of the hardness of a material, calculated from the size of an impression produced under load by a pyramid-shaped diamond indenter. Devised in the 1920s by engineers at Vickers, Ltd., in the United Kingdom, the diamond pyramid hardness test, as it also became known, permitted the establishment of a continuous scale of comparable numbers that accurately reflected the wide range of harnesses found in steels. The indenter employed in the Vickers test is a square-based pyramid whose opposite sides meet at the apex at an angle of 136° . The diamond is pressed into the surface of the material at loads ranging up to approximately 120 kilograms-force, and the size of the impression (usually no more than 0.5 mm) is measured with the aid of a calibrated microscope. The Vickers number (VHN) is calculated using the following formula :

$$\text{VHN} = 1.8544(\text{F}/\text{D}^2)$$

with **F** being the applied load (measured in kilograms-force) and **D²** the area of the indentation (measured in square millimeters). The applied load is usually specified when **HVN** is cited. The Vickers test is reliable for measuring the hardness of metals, and also used on ceramic materials. The Vickers indenter is made of diamond, the diamond material of the indenter has an advantage over other indenters because it does not deform over time and use. The impression left by the Vickers indenter is a dark square on a light background. The Vickers impression is more easily "read" for area size than the circular impression of the Brinell method. Like the Brinell test, the Vickers number is determined by dividing the load by the surface area of the indentation (**H = P/A**). The load varies from 1 to 120 kilograms. To perform the Vickers test, the specimen is placed on an anvil that has a screw threaded base. The anvil is turned raising it by the screw threads until it is close to the point of the indenter. With start lever activated, the load is slowly applied to the indenter. The load is released and the anvil with the specimen is lowered. The operation of applying and removing the load is controlled automatically. Several loadings give practically identical hardness numbers on uniform material, which is much better than the arbitrary changing of scale with the other hardness machines. A filar microscope is

swung over the specimen to measure the square indentation to a tolerance of plus or minus **1/1000** of a millimeter. Measurements taken across the diagonals to determine the area are averaged. The correct Vickers designation is the number followed "HVN" (Hardness Vickers Number). The advantages of the Vickers hardness test are that extremely accurate readings can be taken, and just one type of indenter is used for all types of metals and surface treatments. Although thoroughly adaptable and very precise for testing the softest and hardest of materials, under varying loads, the Vickers machine is a floor standing unit that is rather more expensive than the Brinell or Rockwell machines.



Comparison of hardness measurements :

The table (1) following explain the conversion between Rockwell, Brinell and Vickers hardness testing values. Also this table show the approximate tensile strength corresponding values to those hardness values. While table (2) explain the hardness of different main products and material which can be tested with the particular method .

Table (1) :Hardness units conversion and corresponding tensile strength to them ..

Rockwell C Scale	Brinell Hardness	Vickers Hardness	Tensile Strength (approx.)		Rockwell C Scale	Brinell Hardness	Vickers Hardness	Tensile Strength (approx.)	
Brale Penetrator	10mm Tungsten Carbide Ball	Pyramidic Diamond			Brale Penetrator	10mm Tungsten Carbide Ball	Pyramidic Diamond		
150kgf	3.000kgf	10kgf	ksi	kg/mm ²	150kgf	3.000kgf	10kgf	ksi	kg/mm ²
67	-	900	-	-	43	400	423	201	141
66	-	865	-	-	42	390	412	196	138
65	739	832	-	-	41	381	402	191	134
64	722	800	-	-	40	371	392	186	131
63	705	772	-	-	39	362	382	181	127
62	688	746	-	-	38	353	372	176	124
61	670	720	-	-	37	344	363	172	121
60	654	697	-	-	36	336	354	167	118
59	634	674	329	232	35	327	345	163	114
58	615	653	319	224	34	319	336	159	112
57	595	633	307	216	33	311	327	154	109
56	577	613	297	209	32	301	318	149	105
55	560	595	288	202	31	294	310	146	102
54	543	577	279	196	30	286	302	142	99
53	525	560	269	189	29	279	294	138	97
52	512	544	262	184	28	271	286	134	94
51	496	528	253	178	27	264	279	130	92
50	481	513	245	172	26	258	272	127	89
49	469	498	238	167	25	253	266	125	88
48	455	484	231	162	24	247	260	122	85
47	443	471	224	158	23	243	254	120	84
46	432	458	218	153	22	237	248	116	82
45	421	446	212	149	21	231	243	113	80
44	409	434	206	145	20	226	238	111	78

Table (2) : Explain the hardness of different products and material which can be tested by particular method .

Brinell	Rockwell	Vickers
<p>1-Structural steel and other rolled sections</p> <p>2-Most castings, including steel, cast iron, and aluminum</p> <p>3-Most forgings</p>	<p>1-Finished parts. such as bearings, bearing races, valves, nut, bolts, gears, pulleys, rolls, pins, pivots, stops, etc.</p> <p>2-Cutting tools, such as saws, knives, chisels, scissors</p> <p>3-Forming tools</p> <p>4-Small castings and forgings</p> <p>5-Steel metal</p> <p>6-Large-diameter wire</p> <p>7-Electrical contact</p> <p>8-Plastic shell or parts</p> <p>9-Case-hardened parts</p> <p>10-Cemented carbides</p>	<p>Same as Rockwell and Rockwell superficial except where higher accuracy or shallower penetration is necessary, as in:</p> <p>1-Thin case-hardened parts, 0.005to0.010 in.</p> <p>2-Thin materials down to 0.005 in.</p> <p>3-Highly finished parts to avoid a removal operation</p> <p>4-Thin sections such as tubing</p> <p>5-Weak structures</p> <p>6-Plating thickness</p>

Tensile test and Strain-Stress Diagram

Strain-Stress Diagram expresses a relationship between a load applied to a material and the deformation of the material, caused by the load. Strain-Stress Diagram is determined by **tensile test**. Tensile tests are conducted in **tensile test machines**, providing controlled uniformly increasing tension force, applied to the specimen. The specimen's ends are gripped and fixed in the machine and its **gauge length L_0** (a calibrated distance between two marks on the specimen surface) is continuously measured until the rupture. Test specimen may be round or flat in the cross-section. In the round specimens it is accepted,

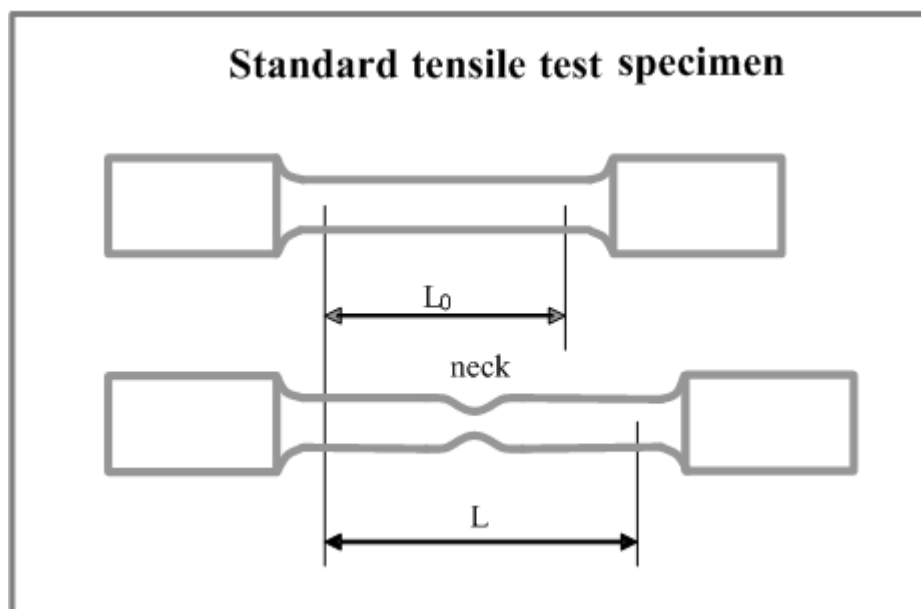
that $L_0 = 5 * \text{diameter}$.

The specimen deformation (**strain**) is the ratio of the increase of the specimen gauge length to its original gauge length:

$$\delta = (L - L_0) / L_0$$

Tensile stress is the ratio of the tensile load **F** applied to the specimen to its original cross-sectional area **S₀**:

$$\sigma = F / S_0$$



The initial straight line (**OP**) of the curve characterizes proportional relationship between the stress and the deformation (strain). The stress value at the point **P** is called the **limit of proportionality**:

$$\sigma_p = F_p / S_0$$

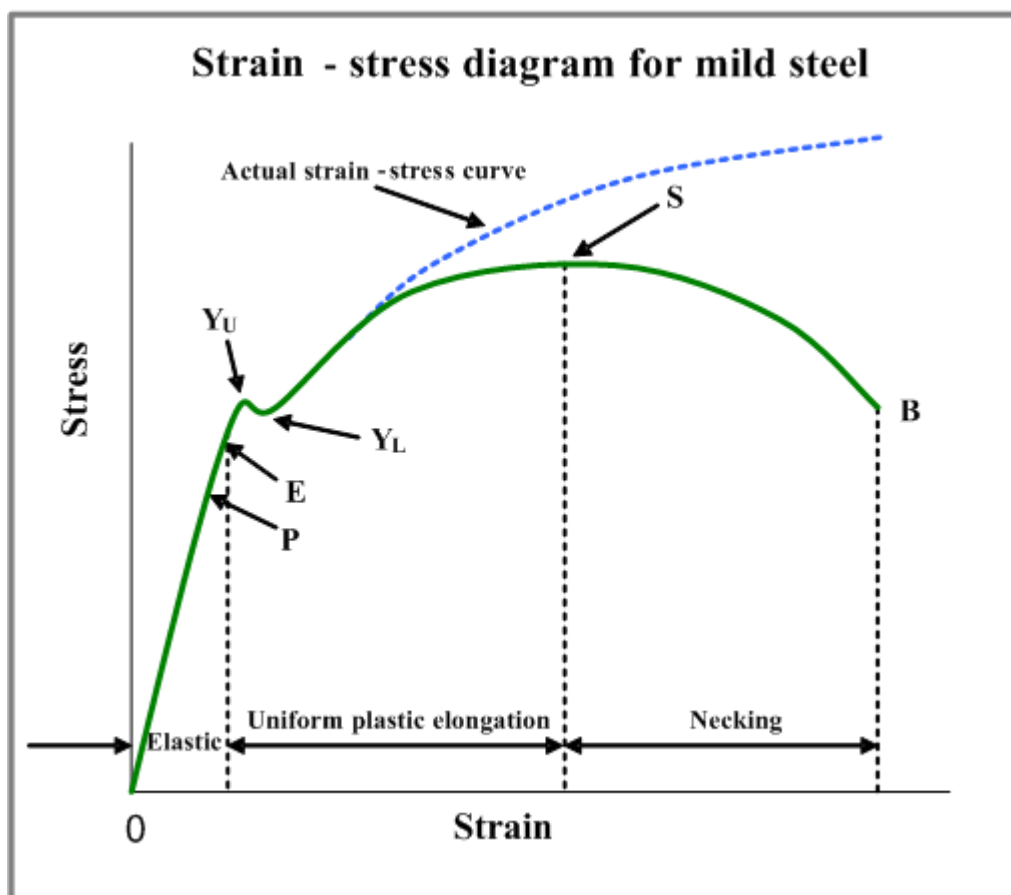
This behavior conforms to the **Hook's Law**:

$$\sigma = E \cdot \delta$$

Where **E** is a constant, known as **Young's Modulus** or **Modulus of Elasticity**. The value of Young's Modulus is determined mainly by the nature of the material and is nearly insensitive to the heat treatment and composition. Modulus of elasticity determines **stiffness** - resistance of a body to elastic deformation caused by an applied force. The line **OE** in the strain-stress curve indicates the range of **elastic deformation** – removal of the load at any point of this part of the curve results in return of the specimen length to its original value. The elastic behavior is characterized by the **elasticity limit** (stress value at the point **E**):

$$\sigma_{el} = F_E / S_0$$

For the most materials the points **P** and **E** coincide and therefore $\sigma_{el} = \sigma_p$.



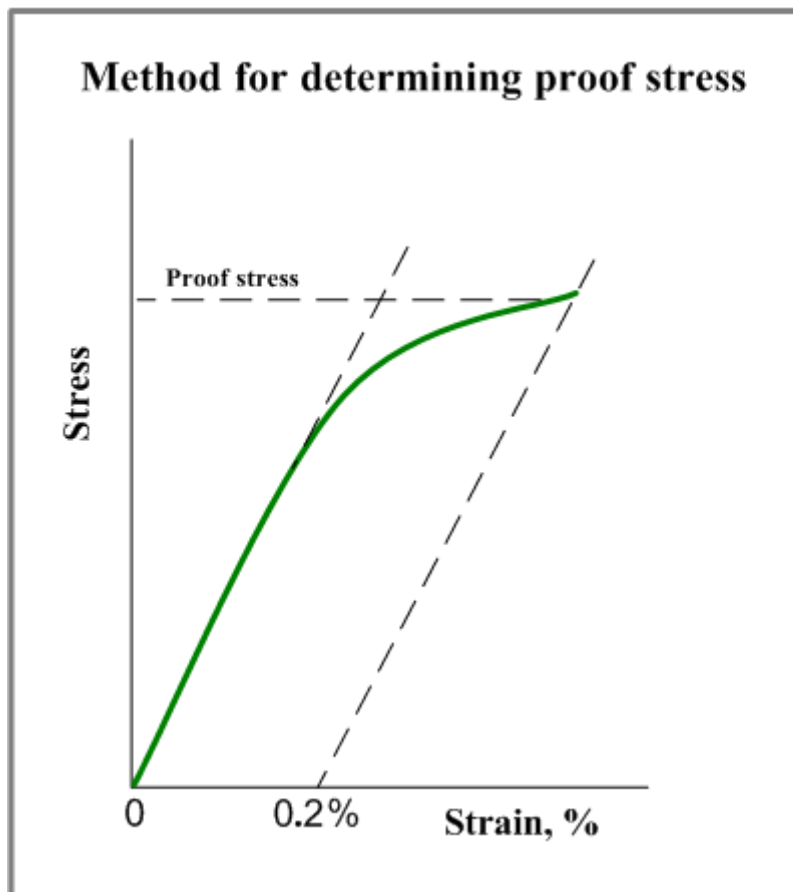
A point where the stress causes sudden deformation without any increase in the force is called **yield limit (yield stress, yield strength)**:

$$\sigma_y = F_Y / S_0$$

The highest stress (point Y_U), occurring before the sudden deformation is called **upper yield limit**. The lower stress value, causing the sudden deformation (point Y_L) is called **lower yield limit**. The commonly used parameter of yield limit is actually lower yield limit. If the load reaches the yield point the specimen undergoes **plastic deformation** – it does not return to its original length after removal of the load. Hard steels and non-ferrous metals do not have defined yield limit, therefore a stress, corresponding to a definite deformation (0.1% or 0.2%) is commonly used instead of yield limit. This stress is called **proof stress** or **offset yield limit (offset yield strength)**:

$$\sigma_{0.2\%} = F_{0.2\%} / S_0$$

The method of obtaining the proof stress is shown in the picture.



As the load increase, the specimen continues to undergo plastic deformation and at a certain stress value its cross-section decreases due to “necking” (point S in the strain-stress diagram). At this point the stress

reaches the maximum value, which is called **ultimate tensile strength (tensile strength)**:

$$\sigma_t = F_S / S_0$$

Continuation of the deformation results in breaking the specimen - the point B in the diagram. The actual strain-stress curve is obtained by taking into account the true specimen cross-section instead of the original value. Other important characteristic of metals is **ductility** - ability of a material to deform under tension without rupture. Two ductility parameters may be obtain from the tensile test:

Relative elongation - ratio between the increase of the specimen length before its rupture and its original length:

$$\delta = (L_m - L_0) / L_0$$

Where L_m - maximum specimen length.

Relative reduction of area - ratio between the decrease of the specimen cross-section area before its rupture and its original cross-section area:

$$\psi = (S_0 - S_{\min}) / S_0$$

Where S_{\min} - minimum specimen cross-section area

Solved example :

A tensile test was done on a stander tensile specimen which was made from carbon steel .the specimen with circular cross-sectional area has a diameter equal to (20 mm) .The applied loads and the corresponded resulted elongation during the test are listed in the table (1) bellow . Draw the load – elongation curve then determine each of the following :

- 1- Yield stress .
- 2- Tensile strength .
- 3- The length of the specimen .
- 4- Percentage elongation .
- 5- Elastic modulus .

Table (1) : Show the applied loads and the corresponded resulted elongations during the tensile test .

100	115	125	120	110	85	75	75	37.5	Load ($N \times 10^3$)
32	29	24	18	12	4	1.4	0.12	0.06	Elongation (mm)

Solution :

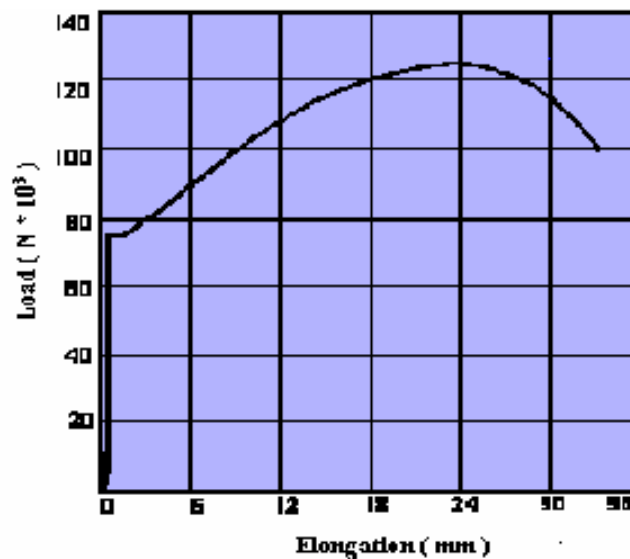


Fig (1) : Illustrate the configuration of the load -elongation curve .

$$A_G = \frac{\pi d^2}{4} = \frac{3.14(20)^2}{4} \approx 314 \text{ mm}^2$$

$$\sigma_y = \frac{F_y}{A_G} = \frac{75 * 1000}{314} \approx 239 \text{ MPa}$$

$$\sigma_T = \frac{F_T}{A_G} = \frac{125 * 1000}{314} \approx 398 \text{ MPa}$$

$$L_G = 5d = 5 * 20 = 100 \text{ mm}$$

$$\% \epsilon = \frac{\Delta L}{L_G} \cdot 100 \% = \frac{32}{100} * 100 \% = 32 \%$$

$$E = \frac{\sigma}{\epsilon}$$

$$= \frac{37.5 * 1000}{314} \div \frac{0.06}{100} \approx 199.044 \text{ GPa}$$

Example (2) :

From the data of elongations and loads that are listed in the table (1) and obtained when a carbon steel rod with a diameter equal to (20 mm) and gauge length equal to (100 mm) . Draw the stress – strain (% Elongation) curve for the tested material .

Table (1) : Show the applied loads and the corresponded resulted elongations during the tensile test .

100	115	125	120	110	85	75	75	37.5	Load (N×10 ³)
32	29	24	18	12	4	1.4	0.12	0.06	Elongation (mm)

Solution :

The solution includes the following steps :

Calculating the value of the stresses by using the following expressions : -1

$$A_0 = \frac{\pi d^2}{4} \text{ ————— (1)}$$

$$\sigma = \frac{P}{A_0} \text{ ————— (2)}$$

2- Calculating the value of the % elongation (strain) by using the following expressions :

$$L_0 = 5d = 5 * 20 = 100 \text{ mm ——— (3)}$$

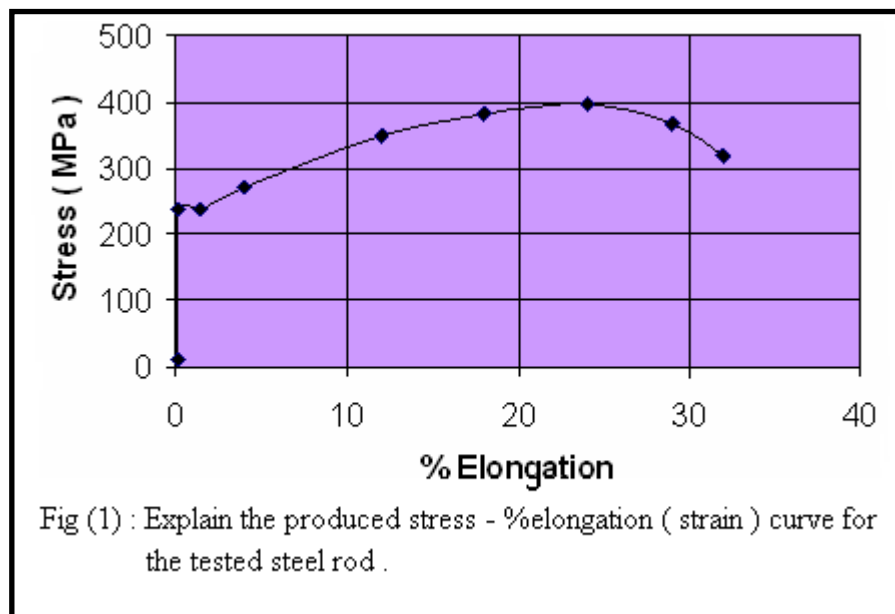
$$\% \epsilon = \frac{\Delta L}{L} 100 \% \text{ ————— (4)}$$

3-The resulted data from the above expressions can be listed as shown in the table (2) bellow .

4- The listed data of stresses and % elongation (strain) thus , can be used to draw the stress - % elongation (strain) curve as shown in fig. (1) .

Table (2) : Explain the calculated values of the stresses & % elongations of the tested material depending upon the values of the applied loads & elongations listed in the table (1) above .

No.	Load (N)	Elongation (mm)	Cross-Sectional Area (A_0) (mm ²)	Gauge Length (L_0) (mm)	Stress (MPa)	% Strain
1	37500	0.06	314	100	11.146	0.06
2	75000	0.12	314	100	238.85	0.12
3	75000	1.4	314	100	238.85	1.4
4	85000	4	314	100	270.70	4
5	110000	12	314	100	350.318	12
6	120000	18	314	100	382.165	18
7	125000	24	314	100	398.089	24
8	115000	29	314	100	366.242	29
9	100000	32	314	100	318.471	32



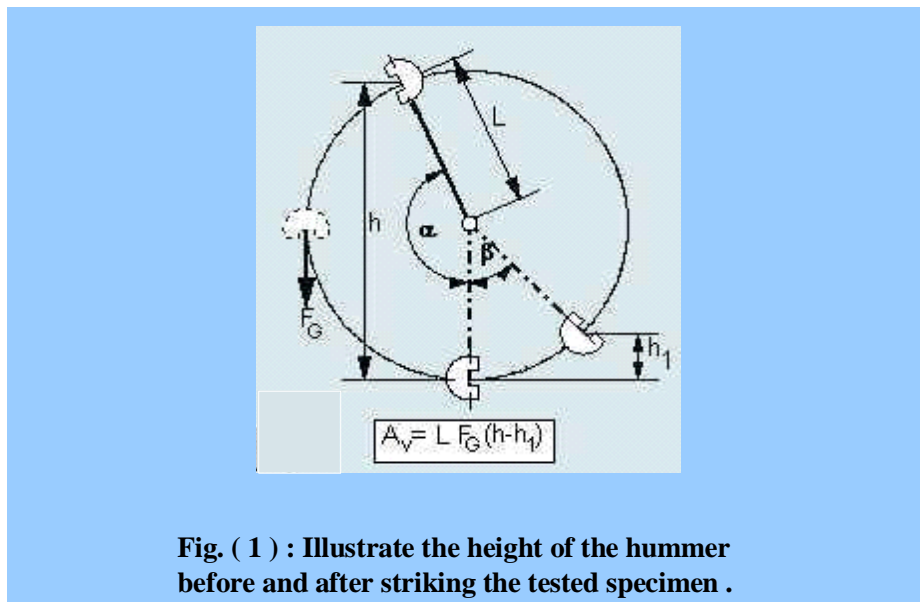
Charpy Impact Test

The aim of the experiment:-

To measure the toughness of the materials which is criteria of the materials resistance to fracture under suddenly applied loads . This test doesn't used for ductile materials .

Basic theory:-

The toughness is measured by the amount of the required energy to break the specimen (the absorbed energy by the specimen during striking it with the dropping hummer) . The working principle Of this experiment is simple. A hammer is raised to a certain height (h) then allowed to drop to blow with the specimen. The hammer swings to the other side like a pendulum with a new height (h₁) as shown in fig. (1) . If the material is brittle the hammer will raise to a larger height when strikes a ductile material specimen . The potential energy before striking process will equal to the weight of the hammer multiplied by it's height (h). After striking , the hammer's potential energy is equal to the result of the multiplication between it's weight and the new height (h₁), hence the difference between these two energies is the amount of the value of the required energy to break the specimen and this value is used later to determine the impact resistance . .



Materials:

A carbon steel specimen with a certain dimensions as shown in fig. (2) is always used in this experiment .

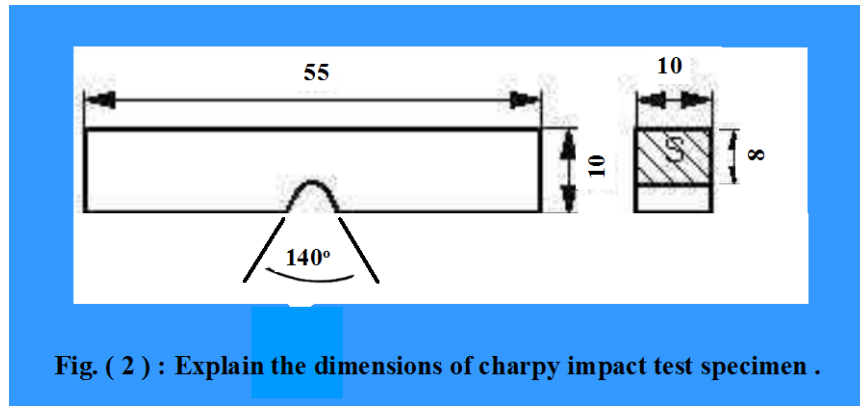


Fig. (2) : Explain the dimensions of charpy impact test specimen .

The Used Instrument

The charpy impact tester as illustrated in fig. (3) is used to do this experiment.

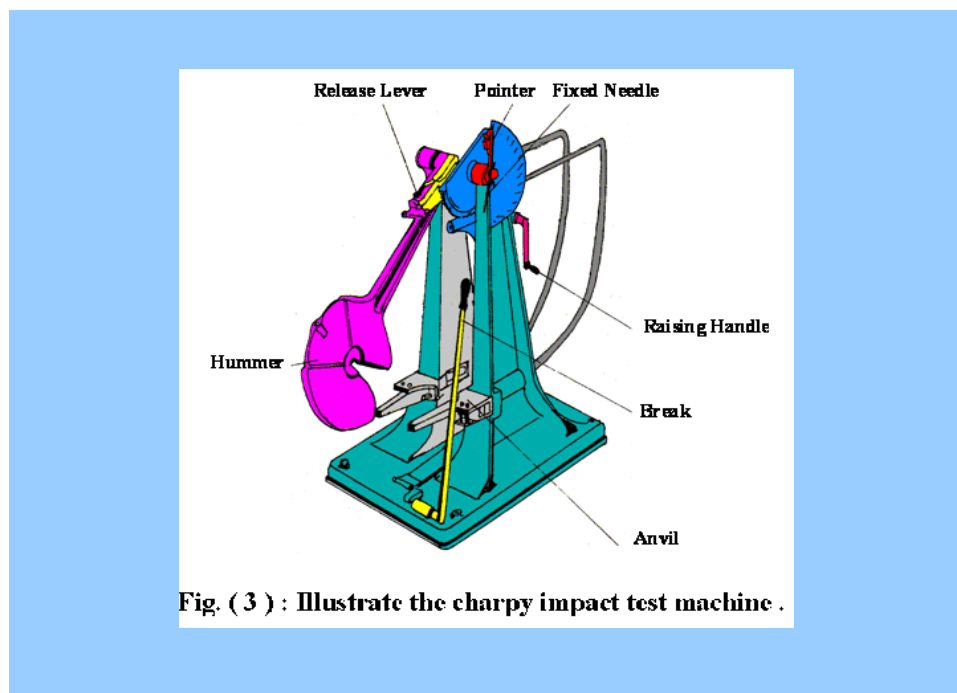
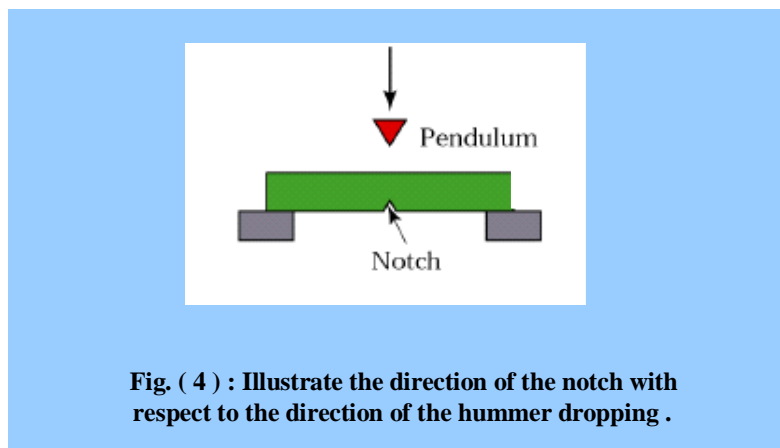


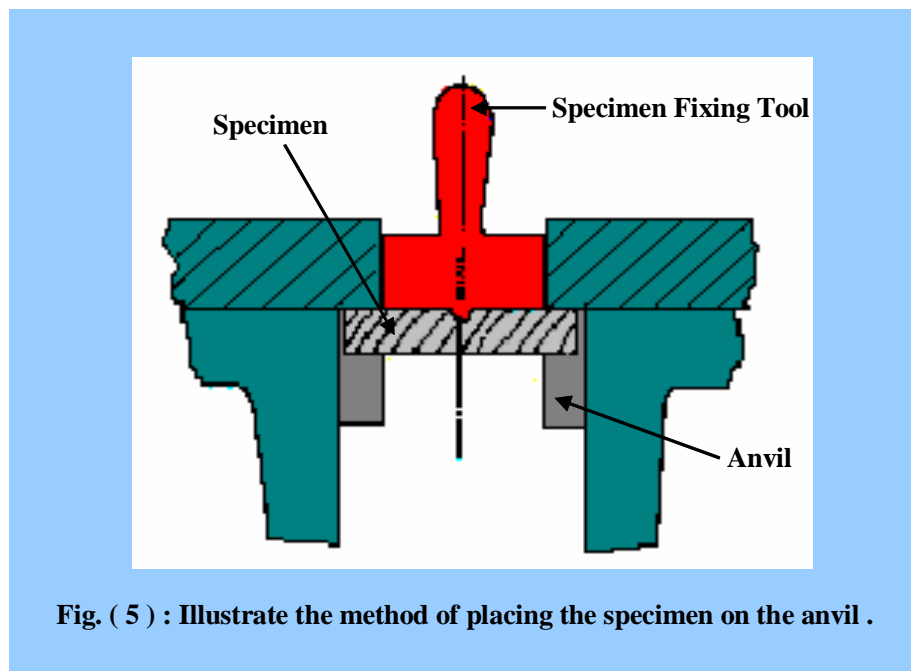
Fig. (3) : Illustrate the charpy impact test machine .

Procedures:

- (1) Confirm whether the maximum pointing needle is fixed at zero point of the dial plate, as shown in fig. (3).
- (2) Bring the hammer dropping and lifting device (release lever) close to hammer and let it hold the hammer tightly then lift the hammer to a little height by rotating the responsible handle gradually and smoothly.
- (3) Put the notched test specimen on the it's place on the anvil where the direction of the notch being in opposition with the hammer dropping direction as illustrated in fig. (4).



- (4) Make sure that the notch is lying in the midpoint of the open space by using specimen fixing tool as shown in fig. (5).



- (5) lift the hammer to 142.5° which gives a blow of about 39Kg.m while it is dropping.
- (6) Remove the hook by pressing on the release lever hence the hammer will drop freely.
- (7) The hammer is swing up after striking the tested specimen ,then stop the hammer from swinging by using the brake system.
- (8) Take the reading of swing up angle particularly the value of angle at which the swing pointer will stop on the gauge

Results:

However , the impact resistance (impact strength) (R) is determined by dividing the value of the absorbed energy by the specimen (E) on the value of specimen's effective cross-sectional area (A_n) (the cross-sectional area at notch) as shown in equation (1) bellow.

$$R = \frac{E}{A_n} \text{ Kgf *m/cm}^2 \text{ ----- (1)}$$

$$E = W \cdot L \cdot (\cos \beta - \cos \alpha) \text{ ----- (2)}$$

Where:-

W:- Weight of hammer (Kg)

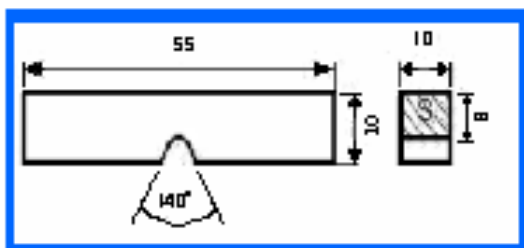
L: - The length of the pendulum (m)

α :- Lifting angle

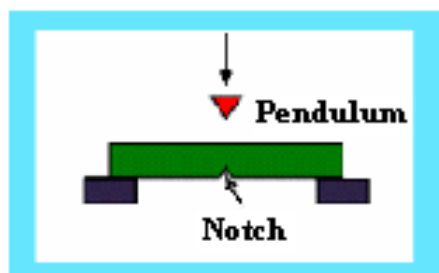
β :- Swing up angle after striking the specimen

Charpy Impact Test

- 1- The amount of shock energy in this method equal to 300J.
- 2- The dimension of the standard test specimen illustrated as bellow.

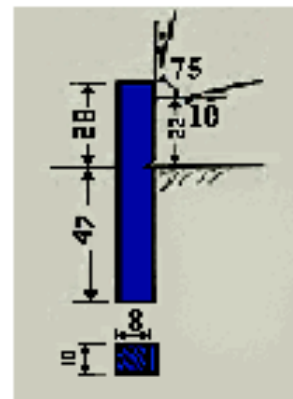


- 3- The specimen is placed in it's position horizontally away that the notch must be in opposite direction of failing pendulum as shown bellow.

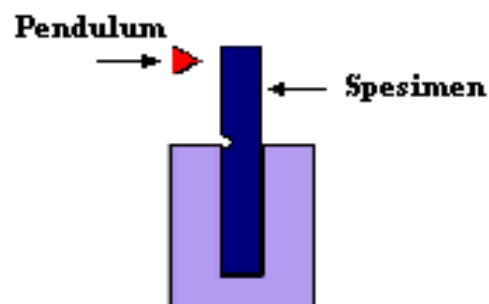


Izod Impact Test

- 1- The amount of shock energy in this method equal to 167J.
- 2- The dimension of the standard test specimen illustrated as below.



- 3- The specimen is fixed by a jaw from one end as lifted (tilted) cantilever in a way that the notch must be toward the failing pendulum and at the fixing plane as shown below.

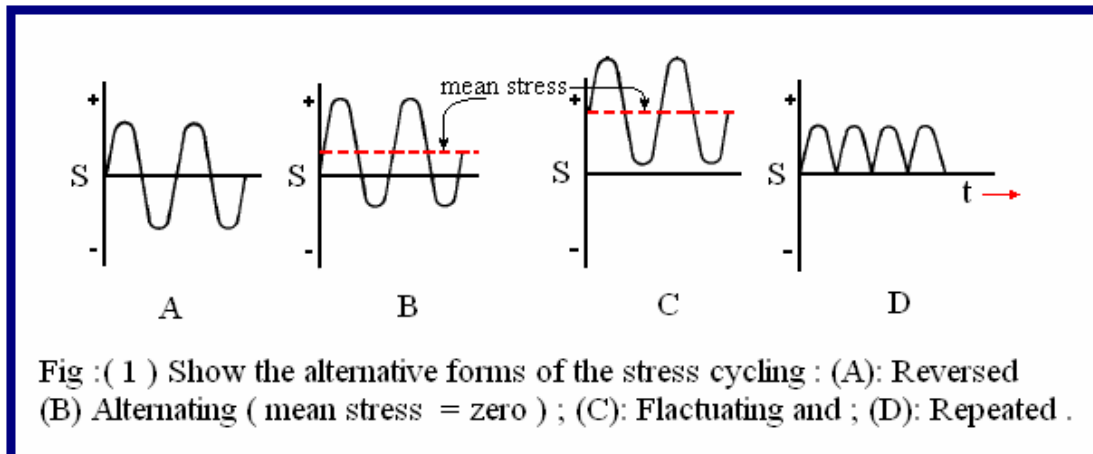


Fatigue failure:

The failure of a material , under repeatedly applied stress is called fatigue . it has been observed that some of the machine parts such as axles , shafts , crankshafts, connecting rods , spring , pinion teeth etc. are subjected to varying stress . it includes the variation in the intensity of the some type of stress as well as different types of stresses (i.e. change of stress from tensile to compressive and vice versa). The varying stresses may be broadly classified into the following four types :

1. the stress varying between two limits of equal value , but of opposite sign .
2. the stress varying between two limits of unequal values , but of opposite sign .
3. the stress varying between zero and a definite value .
4. the stress varying between two limits of unequal values , but of same sign .

The variation in the applied stresses can be also described by terms , reversed; alternating; fluctuating and repeated, as illustrated in fig (1).



Fatigue Life Curves:

Failure due to repeated loading is known as fatigue , fig (2) explain one of the methods where a bending moment when applied on a rotated specimen lead after an interval of time to failure by fatigue . A small crack, a scratch, or some other such minor defect causes localized deformation. This deformation leads to a small crack if one was not initially present. After cyclic loading, that is, loading in the same way multiple times, the crack grows, and eventually the material fails. A fatigue life curve is a graphical representation of the cyclic loading. Simply, **a fatigue life curve**, also known as an **S-N curve** is a plot of the stress amplitude versus the number of cycles the material goes through

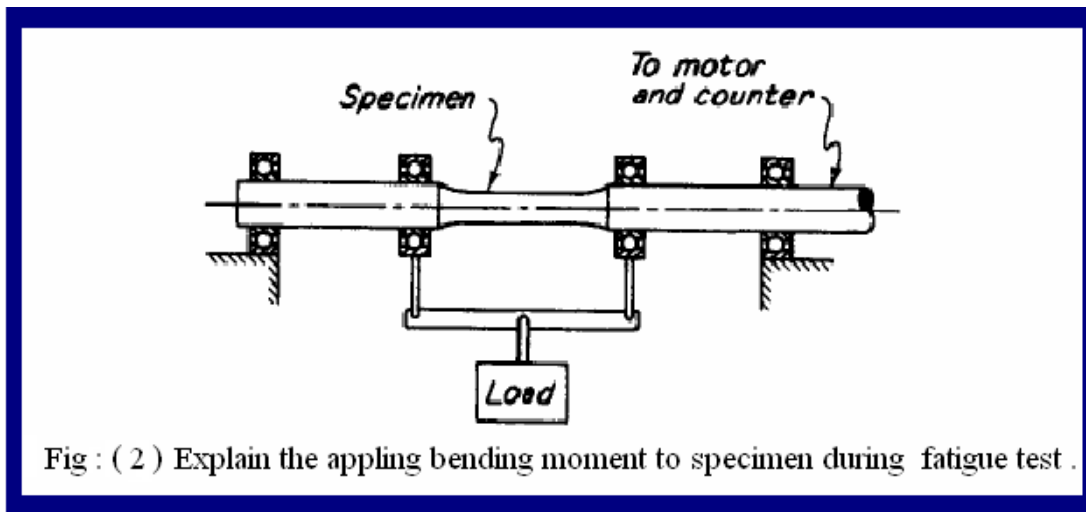


Fig : (2) Explain the applying bending moment to specimen during fatigue test .

before it fails. That is, for a certain stress, the material will fail within a certain number of cycles. Fig (3) is an example of a typical fatigue life curve.

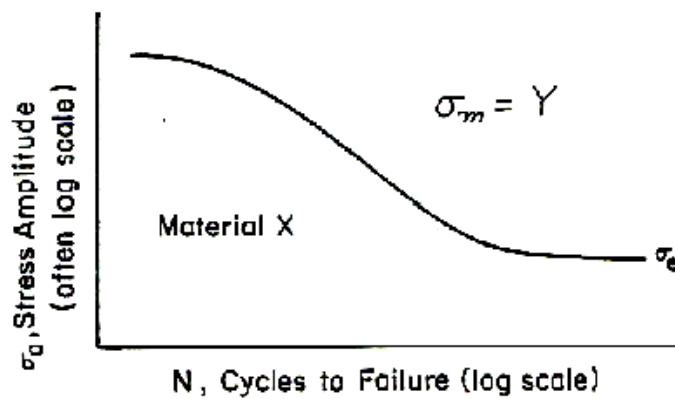


Fig (3) Typical Fatigue Life Curve. From *Mechanical Behavior of Materials Laboratory*, Prepared by Staff of Engineering Science and Mechanics, Virginia Polytechnic Institute, pg. 8-3.

While fig (4) explain the (S-N) curves for steel and aluminum .

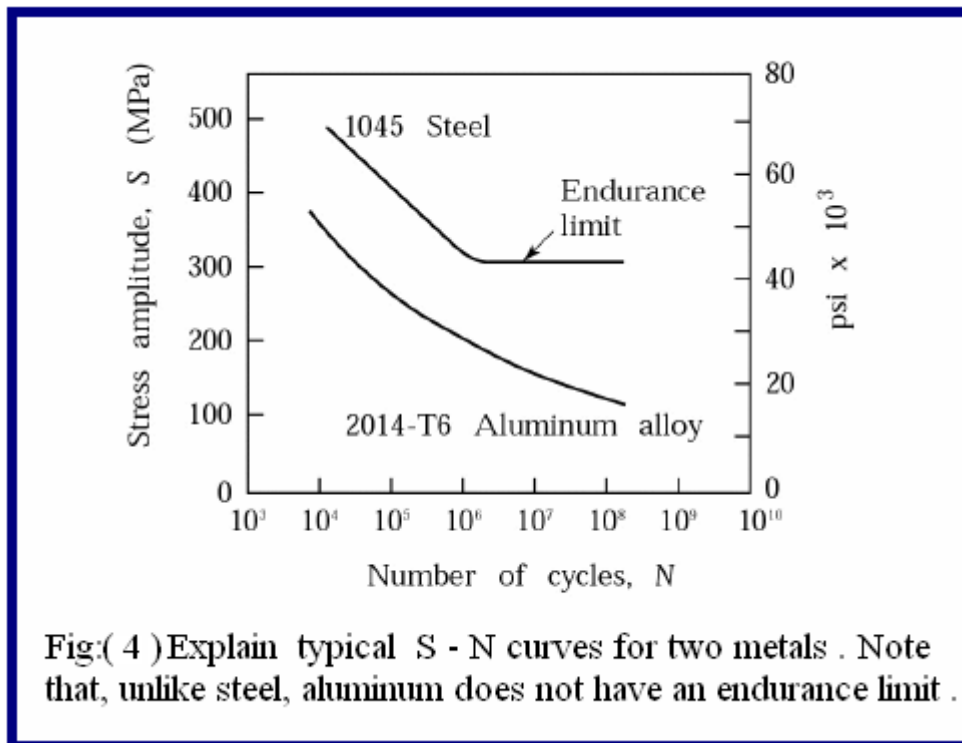


Fig:(4) Explain typical S - N curves for two metals . Note that, unlike steel, aluminum does not have an endurance limit .

Recognition of Fatigue Failure:

The fatigue zone can be described as follows: a smooth rubbed, and velvety appearance, the presence of waves known as "clam-shells" or "oyster-shells", "stop marks" and "beach marks," and the herringbone pattern or granular trace which shows the origin of the crack. In general, stop marks indicate the variations in the rate of crack propagation due to variations in stress amplitude in a cyclic application varying with time. Fig (5) is a schematic representation of the fatigue zone. Fig (6) shows the effects of the stress condition and the case of it's application on the configuration of the rapture zone .

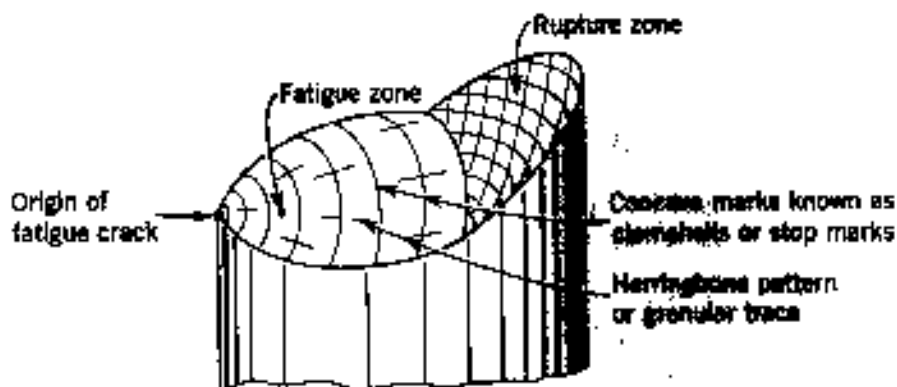




















Fig (5) is a schematic representation of the fatigue zone

Fig : (6) Typical fatigue zone with identifying marks. From *Metal Fatigue: Theory and Design*, ed. A.F. Madayag, pg. 3.

Fig : (6) Describes these relations between the fatigue and rupture zones .

Case \ Stress condition	No stress concentration		Mild stress concentration		High stress concentration	
	Low overstress a	High overstress b	Low overstress c	High overstress d	Low overstress e	High overstress f
1 One - way bending load						
2 Two - way bending load						
3 Reversed bending load rotation load						

CREEP

Introduction:

The mechanical strength of metals decreases with increasing temperature and the properties become much more time dependent. In the past

the operating temperatures in applications like steam power plant, chemical plant and oil refineries seldom exceeded 500°C, but since the development of the gas turbine in the 1940's successive designs have pushed this temperature up to typically 1000 °C. Developments in high temperature alloys with improved high temperature strength and oxidation resistance have had to keep pace with these demands, and applications like rocket engines present greater problems. The strength of **viscoelastic materials** like polymers is very dependent at room temperature on the time factor, i.e. the strain rate applied. This is not so true for metals at low temperatures, but at high temperatures the time factor becomes increasingly important. Metals subjected to a constant load at elevated temperatures will undergo '**creep**', a time dependent increase in length. The terms 'high' and 'low' temperature in this context are relative to the absolute melting temperature of the metal. At **homologous temperatures** of more than 0.5, creep is of engineering significance. Table (1) below illustrates this point.

Table 1: Homologous temperature of 0.5 for lead and tungsten.

Metal	Melting Temperature		0.5 X Melting Temperature	
	^o C	^o K	^o K	^o C
Lead	327	600	300	27
Tungsten	3407	3680	1840	1567

For a low melting point metal like lead, creep becomes significant at about 27°C, i.e. on a hot day. This may cause drainage piping made from lead to sag between its supports or lead plates to creep in a battery. For a high melting point metal like tungsten, temperatures above 1500°C would be needed to produce creep. Tungsten light bulb filaments operate at over 2000°C and do in fact creep under their own weight, with a creep life to rupture of about 1000 hours.

Effect of High Temperature on Metals:

Alloys developed for successful use at high temperatures must cope with the following effects:

- (1) Lower strength.
- (2) Greater atomic and dislocation mobility, assisting dislocation climb and diffusion.
- (3) Higher equilibrium concentration of vacancies.

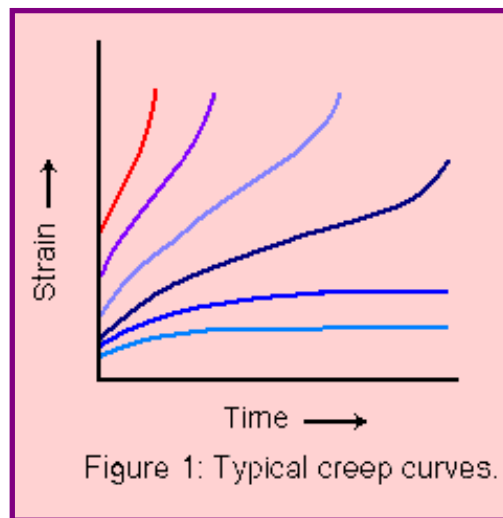
- (4) New deformation mechanisms, such as new slip systems or grain boundary sliding.
- (5) Recrystallisation and grain growth.
- (6) Age hardened alloys will overage by particle coarsening and lose strength.
- (7) Oxidation and intergranular penetration.

High Temperature Mechanical Tests:

Different tests may be required to evaluate high temperature properties, based on the time scale of the service requirements. One of these might include the creep test .

Creep Test:

Measures dimensional changes accurately at constant high temperature and constant load or stress. Useful for long term applications which are strain limited, such as turbine blades. The specimen will have a parallel waisted section, like a tensile specimen, but with screwed ends to avoid slippage in the grips. It is mounted inside a furnace with a sensitive strain measuring device attached, such as an inductance gauge. The figure (1) below illustrate typical creep curves resulted from creep test:



The Creep Curve:

Creep in metals is defined as time dependent plastic deformation at constant stress (or load) and temperature. The form of a typical creep curve of strain versus time is shown in Figure (2). The slope of this curve is the creep rate

$$\text{creep rate} = \frac{d\varepsilon}{dt} \text{ ----- (1)}$$

The curve may show the instantaneous elastic and plastic strain that occurs as the load is applied, followed by the plastic strain which occurs over time. Three stages to the creep curve may be identified:

Primary creep:

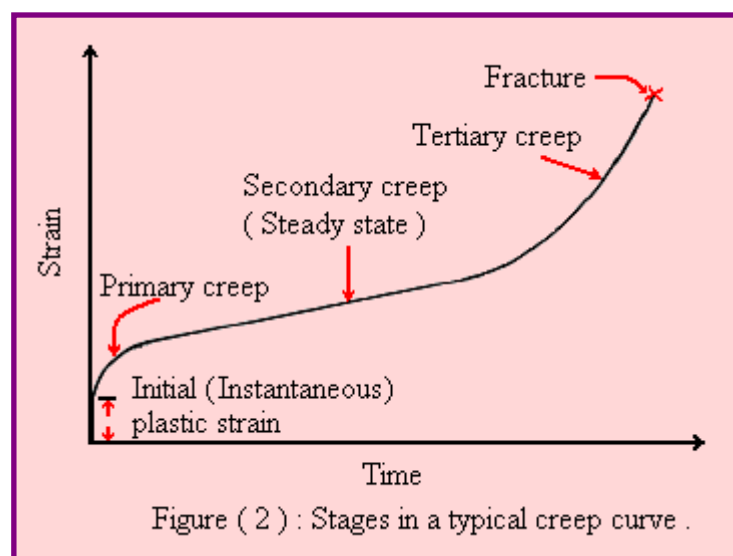
in which the creep resistance increases with strain leading to a decreasing creep strain rate.

Secondary (Steady State) creep:

in which there is a balance between workhardening and recovery processes, leading to a minimum constant creep rate.

Tertiary creep:

in which there is an accelerating creep rate due to the accumulating damage, which leads to creep rupture, and which may only be seen at high temperatures and stresses and in constant load machines. The minimum secondary creep rate is of most interest to design engineers, since failure avoidance is required and in this region some predictability is possible. Constant load machines simulate real engineering situations more accurately, but as the specimen extends its cross section area reduces, leading to a rising stress. Machines designed to reduce the load to compensate for the reduced area and maintain constant stress may produce an extended steady state region. Figure 2: Stages in a typical creep curve.



Models for Creep Curves:

There have been several empirical models proposed for creep curves. Andrade (1914) considered the superposition of a transient term and a viscous creep term, thus:

$$\text{Strain, } \epsilon = \epsilon_0 (1 + \beta t^{1/3}) \exp(\kappa t) \text{ ----- (2)}$$

where t is time and β, κ are constants.

Wyatt (1953), using data on polycrystalline copper, produced:

$$\text{Strain, } \varepsilon = a \log t + bt^n + ct \text{ ----- (3)}$$

where (a, b, c) are constants and

$$n \cong \frac{1}{3}$$

Secondary creep, which occurs as a linear function of time, is strongly dependent on temperature and stress. Since creep is a **thermally activated process**, the minimum secondary creep rate can be described by a fundamental **Arrhenius equation** of the form:

$$\text{Secondary creep rate, } \frac{d\varepsilon}{dt} = A \exp\left(-\frac{Q_0 - v\sigma}{RT}\right) \text{ ----- (4)}$$

Where ; A, v are constants, σ is applied stress, Q_0 is activation energy for creep in Joules per mole, R is the gas constant and T is the absolute temperature. An alternative expression , which separates the stress and temperature terms, is:

$$\text{Secondary creep rate, } \frac{d\varepsilon}{dt} = A\sigma^n \exp\left(-\frac{Q_0}{RT}\right) \text{ ----- (5)}$$

Where :

$$n \cong 3 \rightarrow 8$$

except at low stress where it is approximately (1). Hence the term '**power law creep**'.

Phase diagrams:

Alloys, in engineering, pure metals are rarely used because of their poor physical and mechanical properties. This has led to the development of alloys.

A substance that possesses metallic properties is compound of two or more elements, of which at least one is metal is called an alloy. The base metal of an alloy is the metal present in the greatest proportion, while other metallic or nonmetallic elements present are known as alloying element.

These alloying elements are added to get certain desirable properties which are not found in the base metal.

The type and extent of change of properties depend on whether the alloying elements are insoluble in, dissolve in, or form a new phase with the base metal

Solid solutions :

When homogeneous mixtures of two or more kinds of atoms occur in the solid state, they are known as solid solution.

A solid solution is a single phase, as it is chemically homogeneous and the component atoms cannot be distinguished physically or separated mechanically by ordinary means.

Two kinds of solid solutions are formed:

- 1- Interstitial solid solution.
- 2- Substitution solid solution.

Interstitial solid solution:

These type of solid solution are formed when the solute atoms are very small in comparison with the solvent (matrix) atoms and solute atoms are found in the " holes " or interstices between solvent atoms as shown in (fig -1-a).

In general hydrogen, carbon, and nitrogen and boron which have small atomic diameters can form interstitial solid solutions with the transition metal (e.g. Fe, Ni, Zr, Ti, V, Mo, W,) .the small diameter solute atoms can be dissolved much easily in these metals.

Interstitial solid solutions normally have very limited solubility and generally have limited importance.

Substitution solid solutions:

They are formed when the solute take up the position in the crystal lattice of the solvent metal. The solid solubility is governed by some factors according to Hume- Ruther and these factors are :

- 1- Relative size factor : if the sizes of two metallic atoms differ by less than 15 % , so each of the metals will be able to dissolve in the other metal on order of 10% .for complete solid solubility the size factor difference must be less than 8% . Cu and Ni, and Ag – Au –Pt are examples of binary and ternary systems showing complete solid solubility.
- 2-Chemical affinity factor: the greater the chemical affinity of two metals tends to decrease their solid solubility.
- 3- Relative valence factor: A metal of high valence can dissolve only a small amount of lower valence metal.
- 4- Lattice – type factor: only metals have the same type of lattice (fcc for example)can form a complete series of solutions.

Cu – Ni and Ag-Au-Ni are examples of binary and ternary systems with complete solid solubility.

Substitutional solid solutions may also be ordered or disordered. if the atoms of the solute material occupy similar lattice point with in the crystal structure of the solvent material , this is known as ordered , this is known as disordered solutions (fig-1-b,c) .

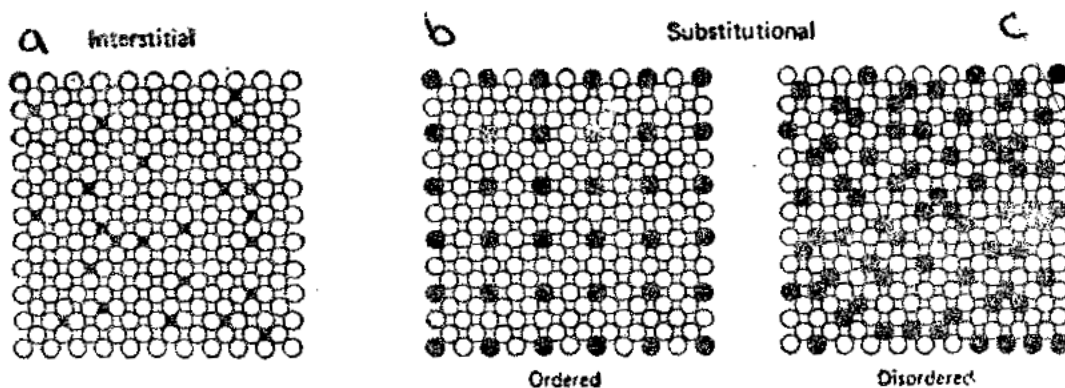


Fig. Interstitial and substitutional (ordered and disordered) solid solutions

Construction of phase diagrams

The phase diagrams are usually constructed from the data of cooling curves obtained by plotting falling in temperature against time for small samples of selected alloys which are allowed to cool under equilibrium condition.

(Fig -2-) illustrated three main types of cooling curves . Each arrestment in cooling curves indicates the start or finish of some sort of phase transformation. in pure metal ,as shown in (fig-2-a) the arrestment zone of the cooling curve is a straight line form A to B at temperature t_1 .

This shows that the transformation from liquid to solid state takes place at constant temperature. All alloys except eutectic mixtures, continue to fall in temperature while phase changes are occurring as shown in (fig – 2-b) for a solid solution. For a multi – phase alloy containing an eutectic mixture, the solidification range is indicated by the interval ABC (fig- 2-c) where the horizontal line BC indicates the eutectic reaction.

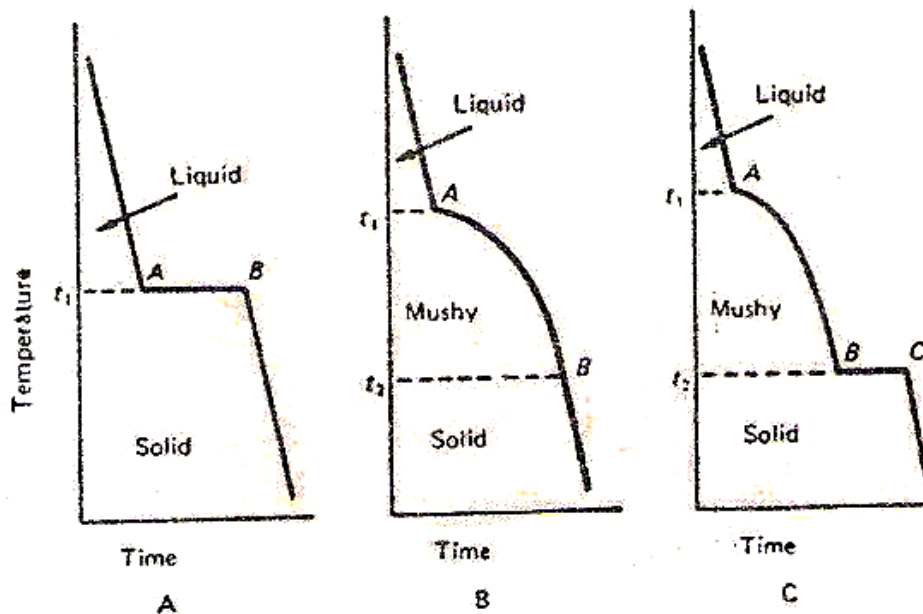


Fig. Cooling curves for pure metals and alloys
(a) Pure metal (b) Solid solution (c) Multi-phase alloy

Thus, an arrestment point occurs at beginning of transformation and again at their point or point of completions. (Fig -- 3) shows how to construct a phase –diagram for alloys of two metals A and B in their various composition us using the data from the cooling curves shown in the left hand side of the diagram.

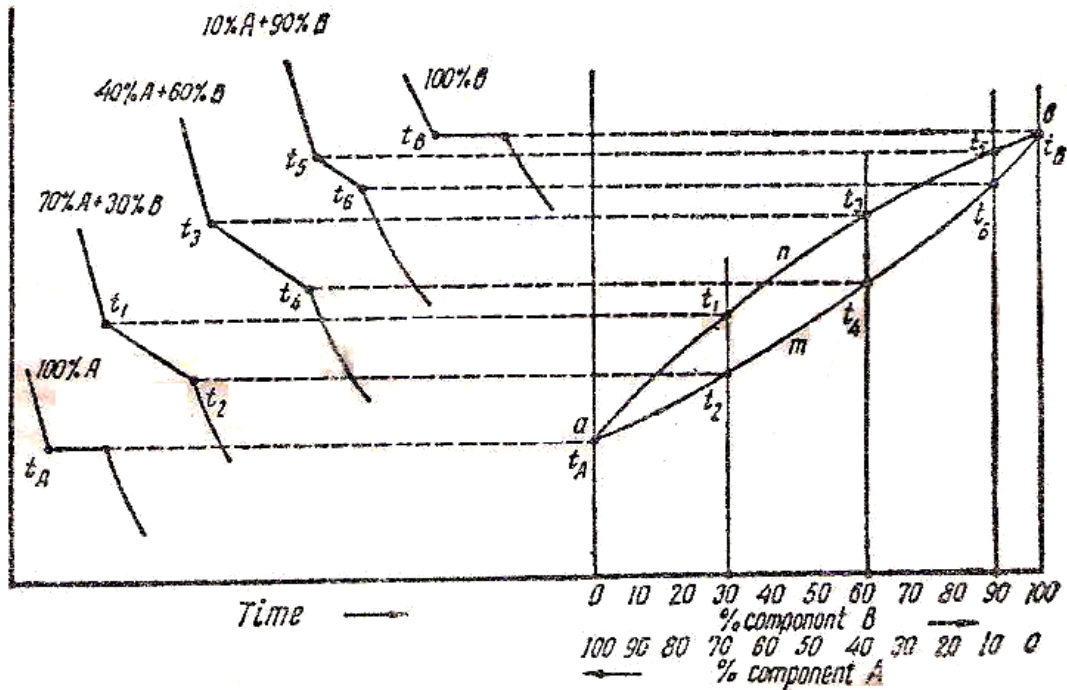


Fig. Construction of a phase diagram

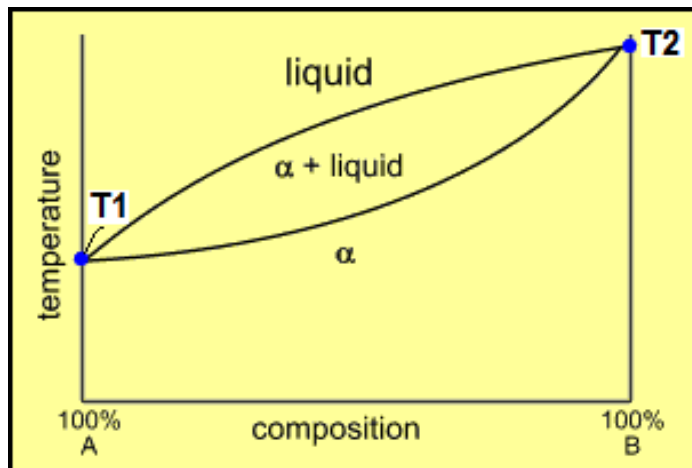
Isomorphous System:

(The phase diagram of two elements which have complete solubility in each other at liquid and solid states)

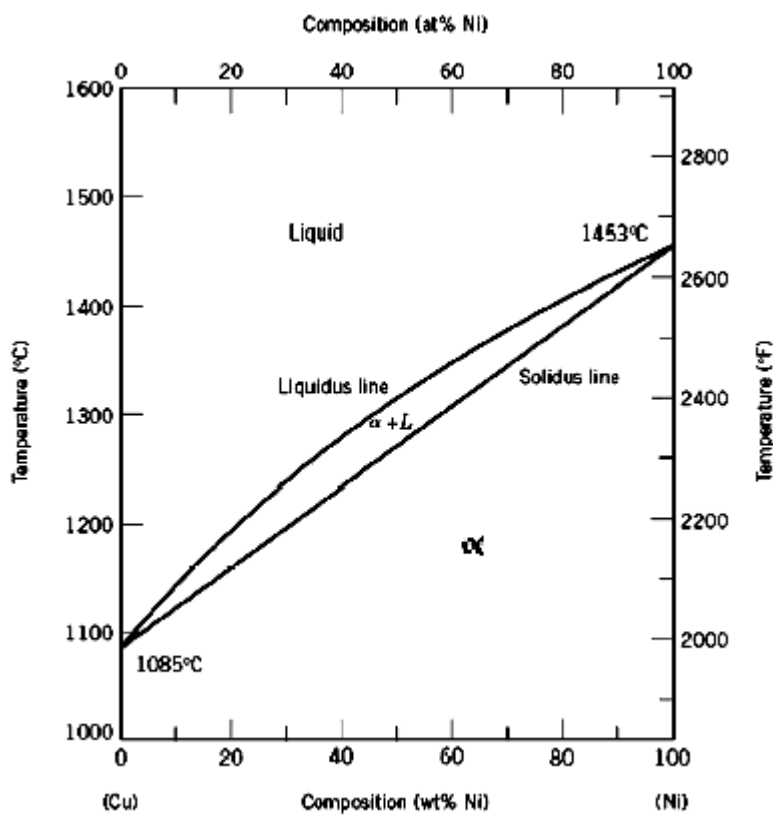
The simplest of two – component or binary alloy system is the isomorphous system in which only a single type of crystal structure is observed and their atoms exhibit similar chemical characteristics for all rates of the components alloys form continuous series of solid solution the alloys system formed between copper (Cu) and nickel (Ni), Cu and Pt, Cu and (Au), Au and Ag, Fe and V and Bi and Sn are of this type. All alloy system of this type exhibits the following characteristics:-

- 1-No eutectic exists within the system.
 - 2-The solid solution formed by the solidification of alloys of varying percentage composition reveal little variation in their mechanical properties while electrical properties and corrosion resistance may alter largely with only minor compositional variations.
 - 3-Alloys of this type cooled under industrial (non - equilibrium) conditions exhibit dendrite segregation or coring (i.e. .there is variation of compositions from inside to the grain binuclear) due to rapid cooling rate.
- An isomorphous system is illustrated in (fig -4) in the left – hand side of the diagram **T₁** is the melting point (MP. of metal A), and **T₂** is (MP.

metal B) of. at any point in the field marked (α) the two metals are completely dissolved in each other that they cannot be distinguished.



(fig -4): Illustrate an isomorphous system.



(fig-5): Illustrate the alloys system formed between copper (Cu) and nickel (Ni).

Eutectic System:

In systems of this type, an eutectic mixture is formed, i.e., two distinct solid phases separate simultaneously and at constant temperature from a single liquid phase.

The phases present in a eutectic mixture may be pure metals or solid solutions that depend upon the type of solubility exhibited by the metals within that system. In general the eutectic mixture within a simple binary alloy system is the lowest melting point mixture within that alloy system. Eutectic system in binary alloy system is divided into two groups:

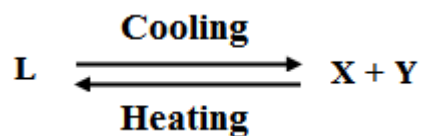
- 1- The system in which two pure metals are complete insoluble in each other in the solid state.
- 2- The system in which partial solid solubility occurs between two metals in the solid state.

Group(1) :

The phase diagram of two metals which have complete solubility at liquid state and incomplete solubility at solid state:

The following points explain the phase or equilibrium diagrams of this type shown in (Fig - 6 -):

- 1- The melting point of metal **X** is indicated by **MP X**, while that of metal **Y** is by **MP Y**.
- 2- The eutectic point is indicated by **EP**, while (**Z-Z**) line is the eutectic line (**isotherm**) and also the solidus that indicates the temperature at which separation of the eutectic will begin for any alloy composition. Alloys located to the left of point **E** are called hypoeutectic alloys and that to the right of point **E** is called hypereutectic alloys.
- 3- liquidus line indicates the start of solidification of any given alloy composition.
- 4- The eutectic reaction can be expressed in the following from:



The cadmium –bismuth alloy system is good example of complete insolubility.

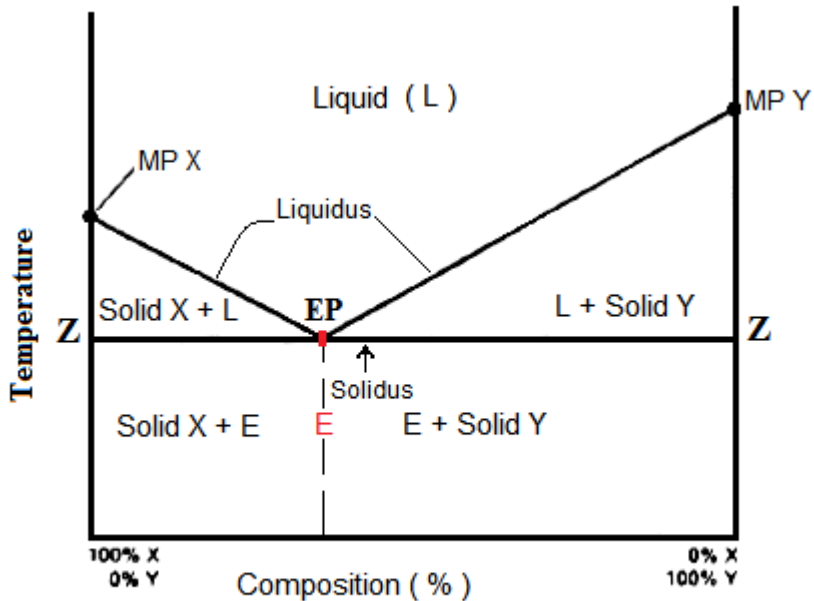
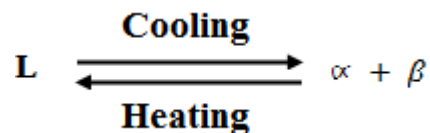


Figure Binary equilibrium diagram for metals that are completely soluble in the liquid state but completely insoluble in the solid state.

Group(2) : complete liquid solubility but partial solid solubility :

If the solvent metal of a binary alloy can dissolve solid solution is formed, and the two metals said to form only a partial solid solubility. This type of solid solubility varies greatly with temperature, In such alloy systems an eutectic mixture is formed of relevant to the type of phase diagram shown in (Fig -7 -) The following points explain the phase or equilibrium diagrams of this type :

- 1-No pure metals exist in a solid alloy of any composition.
- 2-Two solid solution formed .(**B**)is partly soluble in (**A**) , forming (α) solid solution , and (**A**) is partly soluble in (**B**) , forming (β) solid solution ,
- 3-The melting point of metal (**A**) is **MP.A** , while that of metal (**B**) is **MP.B** .
- 4-The eutectic point is indicated by the point (**EP**) , the line (**z-z**) having the point(**E**) is the eutectic isotherm (line).
- 5- The eutectic reaction can be expensed as following:



The lead- Tin alloy system is typical of this group.

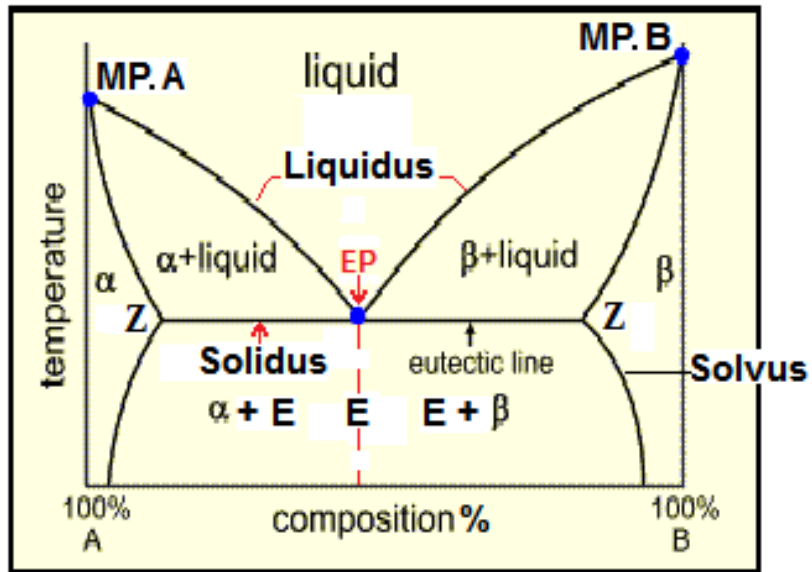


Fig-7 - Eutectic system with partial solid solubility type.

Iron making:

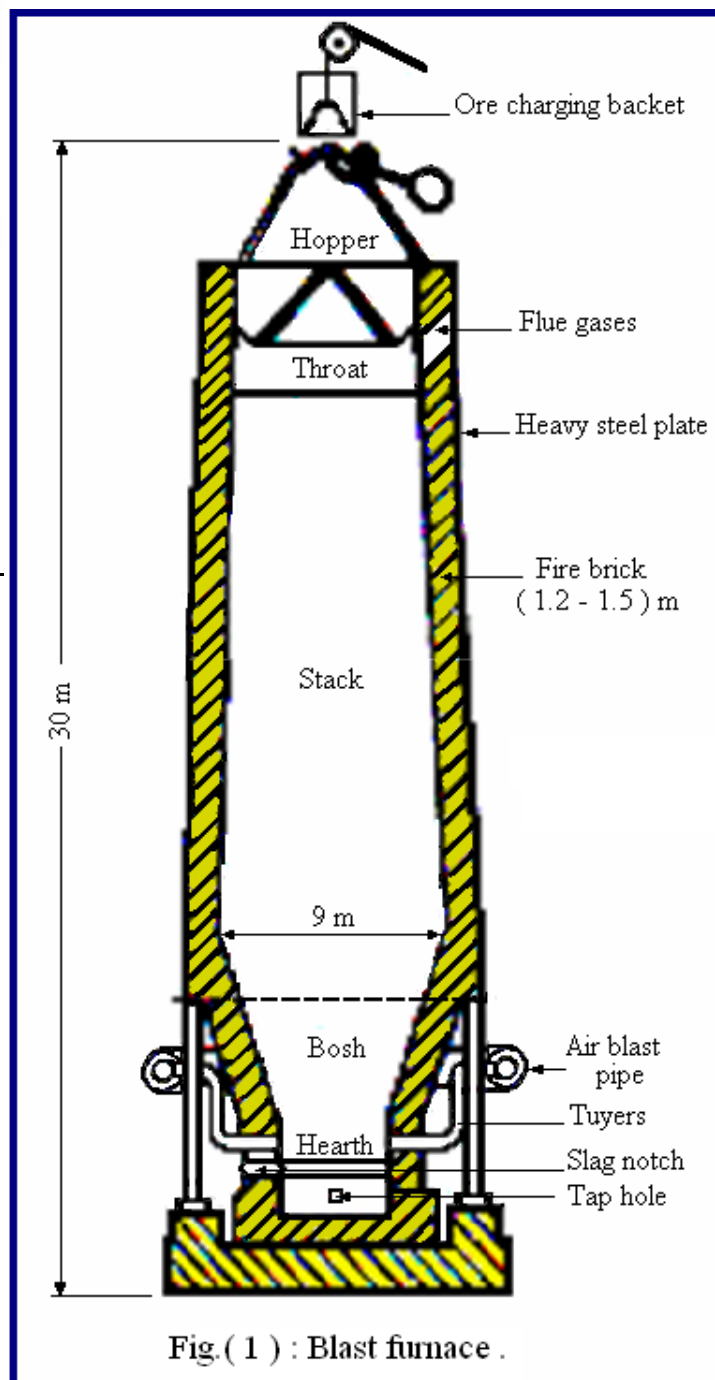
Manufacturing of pig iron :

The pig iron is obtained from the iron ores in the following steps :

- 1- Concentration .
- 2- Calcination or roasting .
- 3- Smelting .

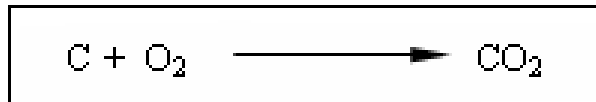
The charge of blast furnace

- 1- Calcined ore 61.5% .
- 2- Coke 30.75% .
- 3- Lime stone 7.75% .



The reaction take place in blast furnace :

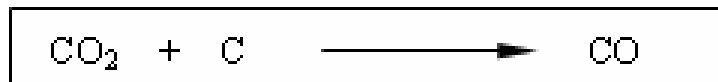
1- In the lower part of the furnace (fusion zone), the oxygen in the hot air blast combines with carbon in the coke as following :



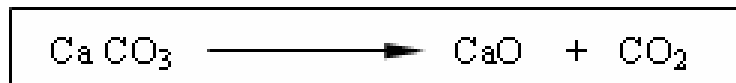
In this zone the temperature is about 1500°C .

2- In the middle part of the furnace (adsorption zone), the following reactions take place :

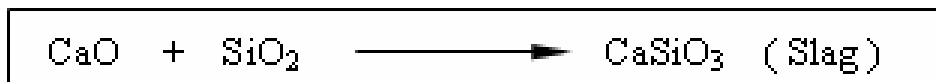
A- In temperatures between ($800 - 1000$) $^\circ\text{C}$, the resulted carbon dioxide rising up and reduced to carbon monoxide as following :



B- Sliding down limestone decomposes to give lime and carbon dioxide as folloing ;

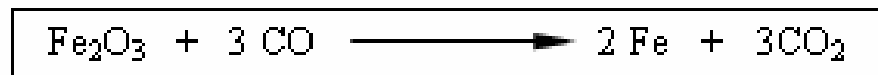


C- The lime acts as flux and combine with silica to form slag as following :

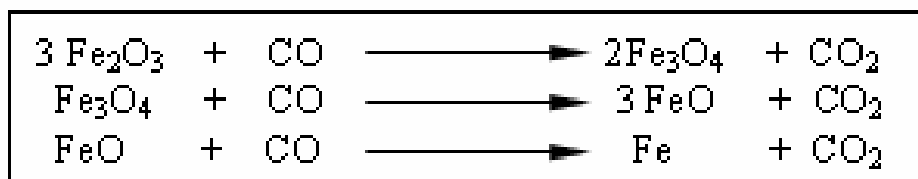


3- In the upper part of the furnace (reduction zone) the iron ore can be reduced by two ways :

A- Direct reduction process as following :



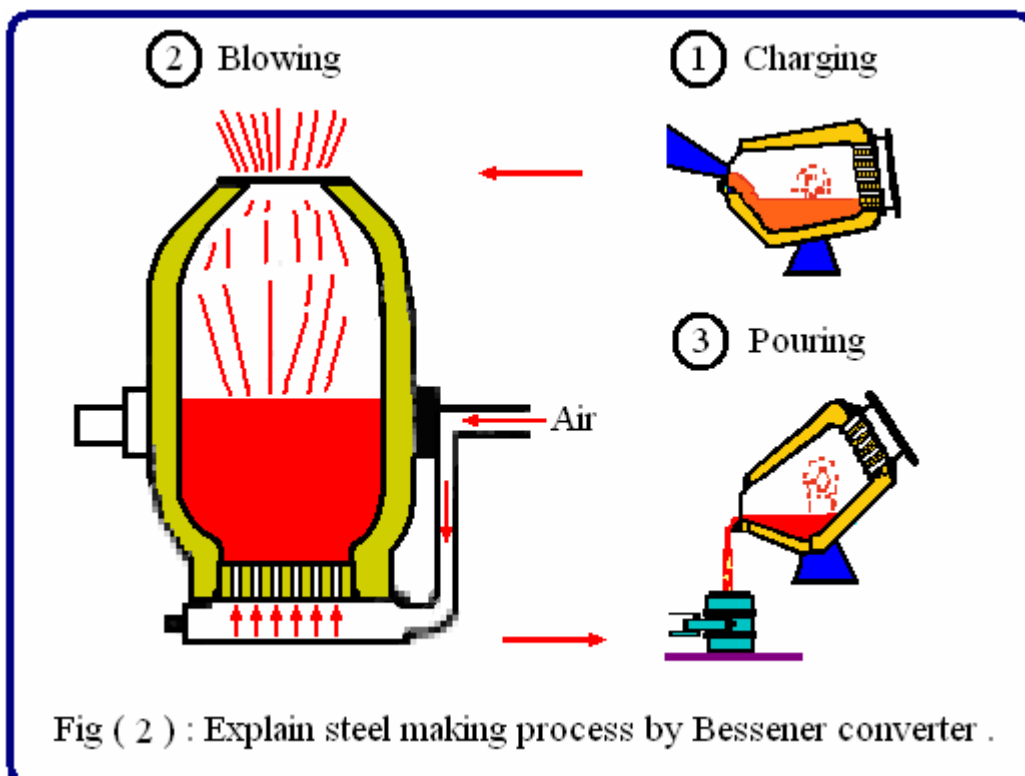
B- Indirect reduction process as following :



Steel making processes:

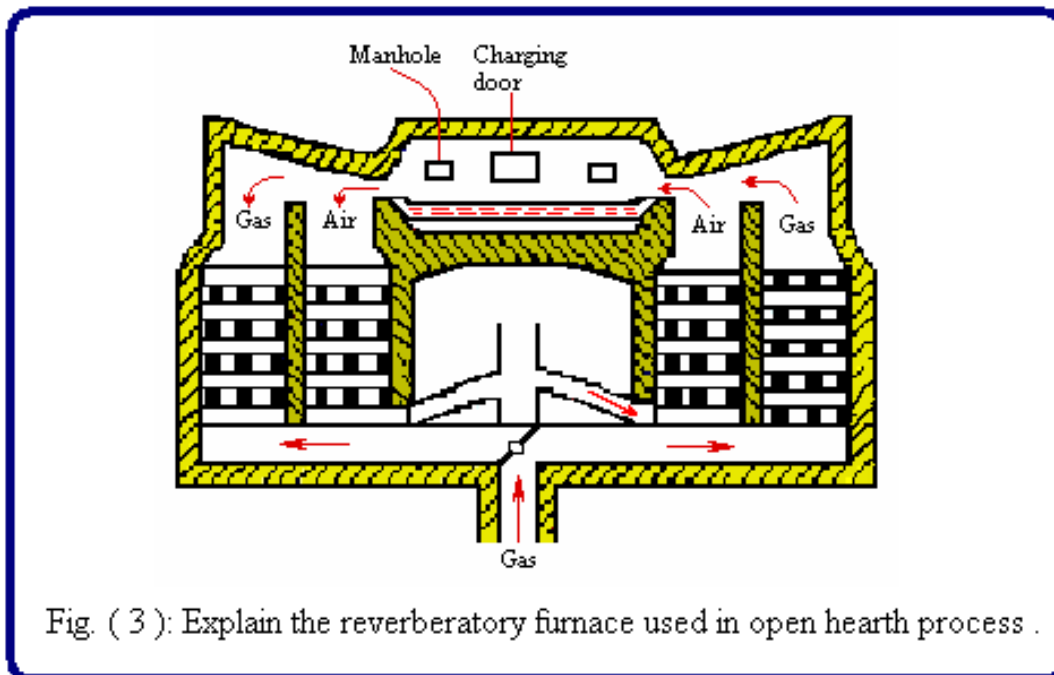
Bessemer steel

In both the Acid Bessemer and Basic Bessemer (or Thomas) processes molten pig iron is refined by blowing air through it in an egg-shaped vessel, known as a converter, of 15-25 tonnes capacity Fig.(2) The oxidation of the impurities raises the charge to a suitable temperature; which is therefore dependent on the composition of the raw material for its heat: 2% silicon in the acid and 1,5-2% phosphorus in the basic process is normally necessary to supply the heat. The "blowing" of the charge, which causes an intense flame at the mouth of the converter, takes about 25 minutes and such a short interval makes exact control of the process a little difficult. The Acid Bessemer suffered a decline in favor of the Acid Open Hearth steel process, mainly due to economic factors which in turn has been ousted by the basic electric arc furnace coupled with vacuum degassing. The Basic Bessemer process is used for making, from a very suitable pig iron, a cheap class of steel, e.g. ship plates, structural sections.



Open-hearth processes

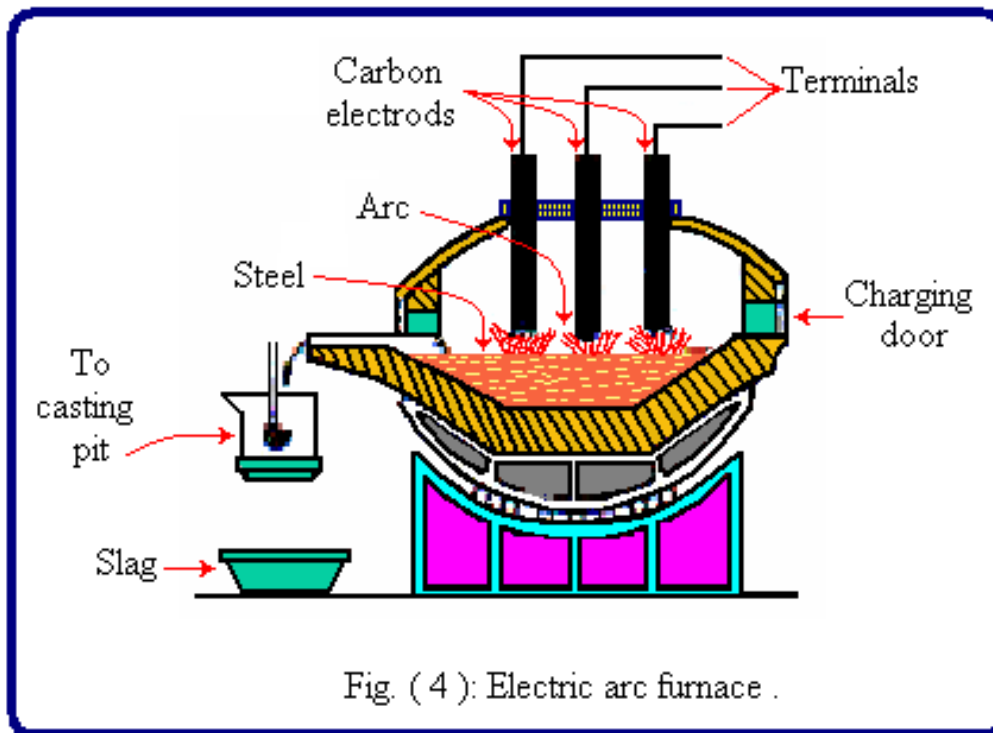
In the Siemens process, both acid and basic, the necessary heat for melting and working the charge is supplied by oil or gas. But the gas and air are preheated by regenerators, two on each side of the furnace, alternatively heated by the waste gases. The furnaces have a saucer-like hearth, with a capacity which varies from 600 tonnes for fixed, to 200 tonnes for tilting furnaces Fig. (3). The raw materials consist essentially of pig iron (cold or molten) and scrap, together with lime in the basic process. To promote the oxidation of the impurities iron ore is charged into the melt although increasing use is being made of oxygen lancing. The time for working a charge varies from about 6 to 14 hours, and control is therefore much easier than in the case of the Bessemer process. The Basic Open Hearth process was used for the bulk of the cheaper grades of steel .



Electric arc process

The heat required in this process is generated by electric arcs struck between carbon electrodes and the metal bath , fig. (4). Usually, a charge of graded steel scrap is melted under an oxidizing basic slag to remove the phosphorus. The impure slag is removed by tilting the furnace. A second limey slag is used to remove sulphur and to deoxidize the metal in the furnace. This results in a high degree of purification and high quality steel can be made, so long as gas absorption due to excessively high

temperatures is avoided. This process is used extensively for making highly alloyed steel such as stainless, heat-resisting and high-speed steels.



Ferrous metals and alloys

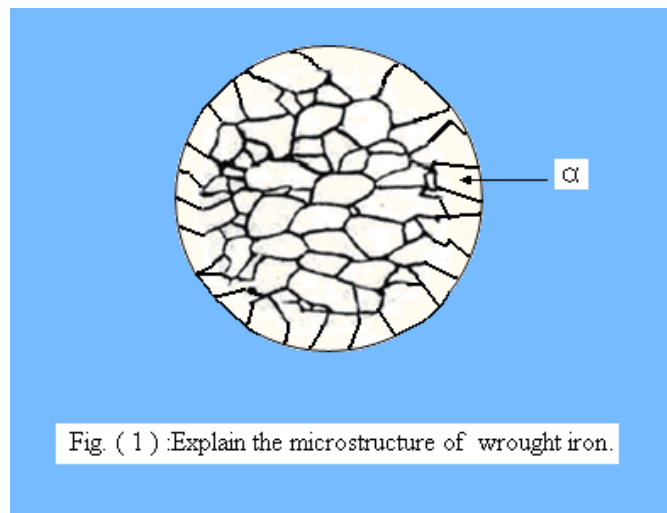
The word ferrous is derived from a Latin word ferrum that mean iron .therefore the ferrous metals may be defined as those metals which contain iron as their main constituent such as pig iron, cast iron ,wrought iron ,steel and their alloys. Pig iron it is the crude form of iron and is used as a raw material for the production of various other ferrous metals such as cast iron ,wrought iron and steel. The pig iron is obtained by smelting iron ores in a blast furnace.

Wrought iron:

It is the purest iron which contain at least 99.5% iron but may contain up to **99.9%** iron the typical composition of a wrought iron is :

carbon-0.020%	silicon-0.120%
sulphar-0.018%	phosphorus -0.020%
slag-0.070%	the remaining is iron.

The wrought iron is malleable and ductile material .it can not stand sudden and excessive shocks. its ultimate tensile strength is reach to 5000 kg/cm² and the ultimate compressive strength is **3000 kg/cm²**, it can be easily forged or welded. the melting point of wrought iron is about **1538°C**. it is used for bolts and nuts ,chains, crane hooks, railways, water and steam pipes. the microstructure of a wrought iron which have a crystalline structure known as ferrate is shown in fig (1) .

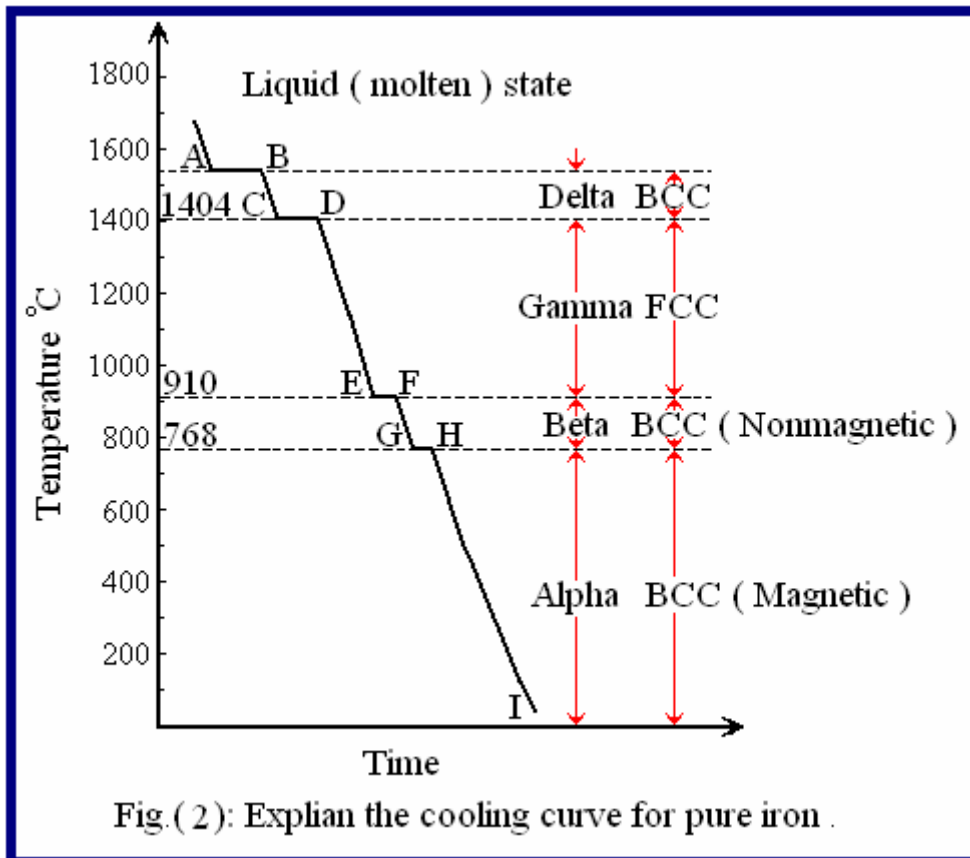


Allotropy of iron:

The study of a given metal ,which can exit in two or more stable but different crystal structures depending upon the condition of temperature or pressure with out any change in chemical composition is known as (γ)

that the atoms of crystalline solids are converted from one crystalline form to another.

The allotropy of iron may be best understood by the study of the cooling process of pure iron from the molten state . If we plot a graph with temperature along vertical axis and time along the horizontal axis we shall obtain a curve as shown in fig (2) .



Steel (carbon steel) :

most of the steel produced now-a days as plain carbon steel . Carbon steel is defined as an alloy of iron and carbon with carbon content up to **1.5 %** and the changes in the properties of the steel will be due to the carbon content mainly and does not contain more than **0.5% Si** and **1% Mn** and a lesser amount from sulphur (**S**) and phosphor (**p**)

The plain carbon steels are divided into the following types depending upon the carbon content :

- 1-Dead mild steel-up to **0.15%C** .
- 2-Low carbon or mild steel - **0.15% C to 0.35%C**.
- 3-Medium carbon steel- **0.35% C to 0.65 % C** .
- 4-High carbon steel - **0.65% C to 1.5 % C** .

Dead mild steels are soft and ductile and cannot be hardened by heat treatment they have uses where high cold formability is required.

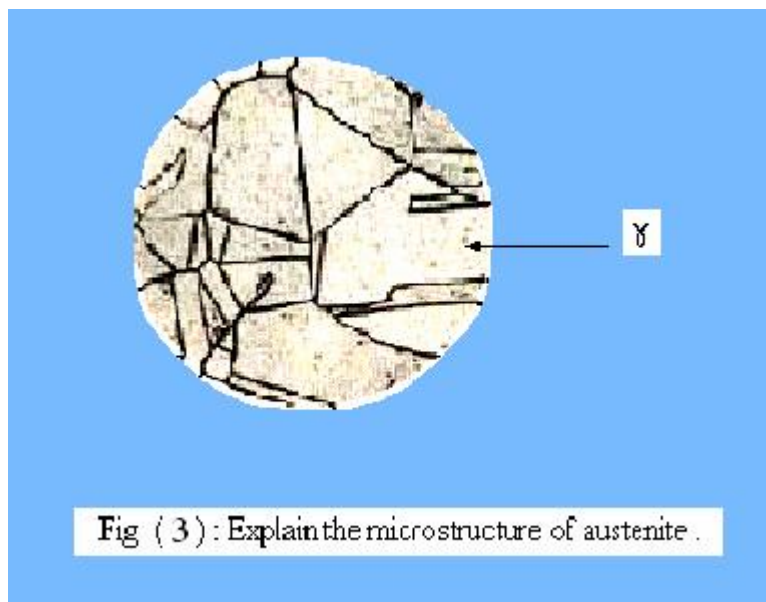
Low carbon or mild steels are general purpose steels .they are ductile and cannot be hardened by heat treatment . Typical application are as joints in buildings body work for cars and ships screws wire food beverage cans and referred to as tinplate.

Medium carbon steels are strong and heat treatable to produce a wide range of properties in the quenched and tempered state they use a where strength and toughness are required e.g. agricultural tools fasteners dynamo and motor shafts crankshafts connecting rods gears . high carbon steels are very strong but with low ductility these steels are used for with standing wear and where hardness is a more necessary requirement than ductility they used for machine tools saws hammers cold chisels punches axes dies drills the main use of high carbon steel is thus as a tool steel.

Micro-constituent of steel:

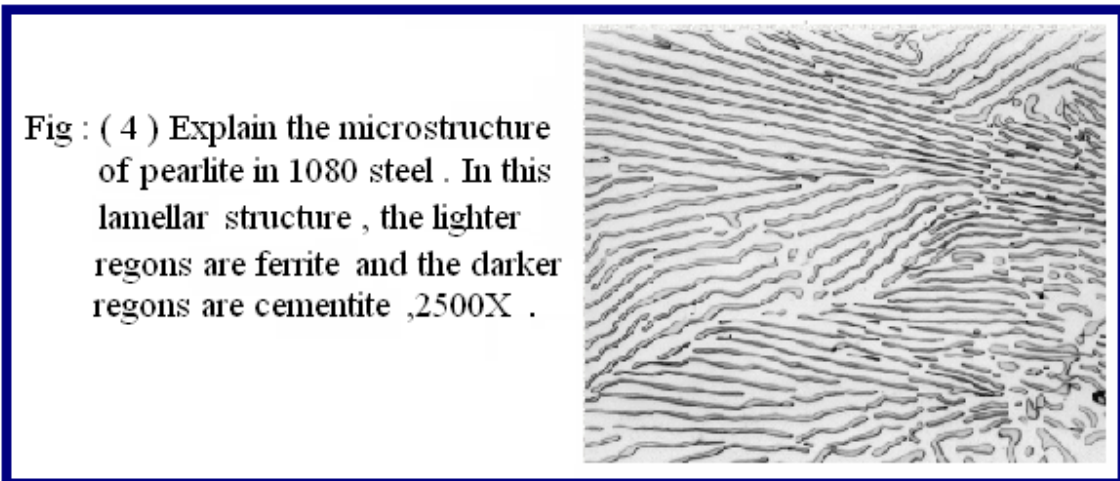
1- **Ferrite (F- α)**:it is the name given to the grains or crystals of solid solution of carbon in alpha iron .the solubility of carbon in alpha iron is **0.025%** at **723°C** .it soft ductile and highly magnetic with a tensile strength approximately **2200kg /cm²**. Fig (1) explain the microstructure of ferrite .

2- **Austenite** :it is a solid solution of carbon in gamma-iron the maximum solubility of carbon austenite is **1.7%** at **1130°C** .it is generally soft ductile and non magnetic ,but denser than ferrite. Fig (3) explain the microstructure of ferrite .



3- **Cementite**:it is a chemical compound from iron and carbon known also as iron carbide (**Fe₃C**),which contains **6.67%C** and **93-33%Fe** by weight .it is found free as network around pearlite grains in steels containing over **0.8% C**. the amount of cementite increase with the

increase in percentage carbon in iron .it is very hard and brittle ,and white in color it is magnetic below **210°C**. in color .it is magnetic below **210°C**.
 4- **Pearlite**:it is a mechanical mixture of about **87%** ferrite and **13%** cementite .it is found in all steels when they are cooled slowly below **723°C** .a steels ,with **0.8%C** ,is wholly pearlite. The structure of pearlite consists of thin alternating plates or lamellae of cementite and ferrite it is stronger than ferrite and may be cut well with cutting tools .it has a tensile strength of **8750kg/cm²** . Fig (4) shows a typical micro structure of ferrite austenite cementite and pearlite.



Iron-carbon equilibrium diagram:

The iron-carbon (or iron-iron carbide) equilibrium diagram is shown in Fig (5) concerns transformation that occur in alloys having composition from pure iron to cementite **6.67%C**.the carbon contents are shown on the horizontal axis and temperature on the vertical axis .whenever an alloy is heated or cooled so that a line on the diagram is crossed ,a phase change occurs.

From this phase diagram Fig (5) we conclude that:

- 1-The percentage of carbon varies from zero to **6.67%C**.
- 2-The iron containing carbon from zero to **1.7%C** is known as steel.
- 3-The steels which contain less than **0.8%C** known as hypo –eutectoid steels. They are composed of ferrite (**Fe- α**)and pearlite (**P**) after transformation
- 4-The steel which contain **0.8%C** known as eutectoid steel which composed entirely from pearlite after transformation .
- 5-The steel which contain above **0.8%C** known as hypereutectoid steels transform into cementite (**Fe₃C**) and pearlite.
- 6-The iron containing carbon more than **1.7%C** is known as cast iron.

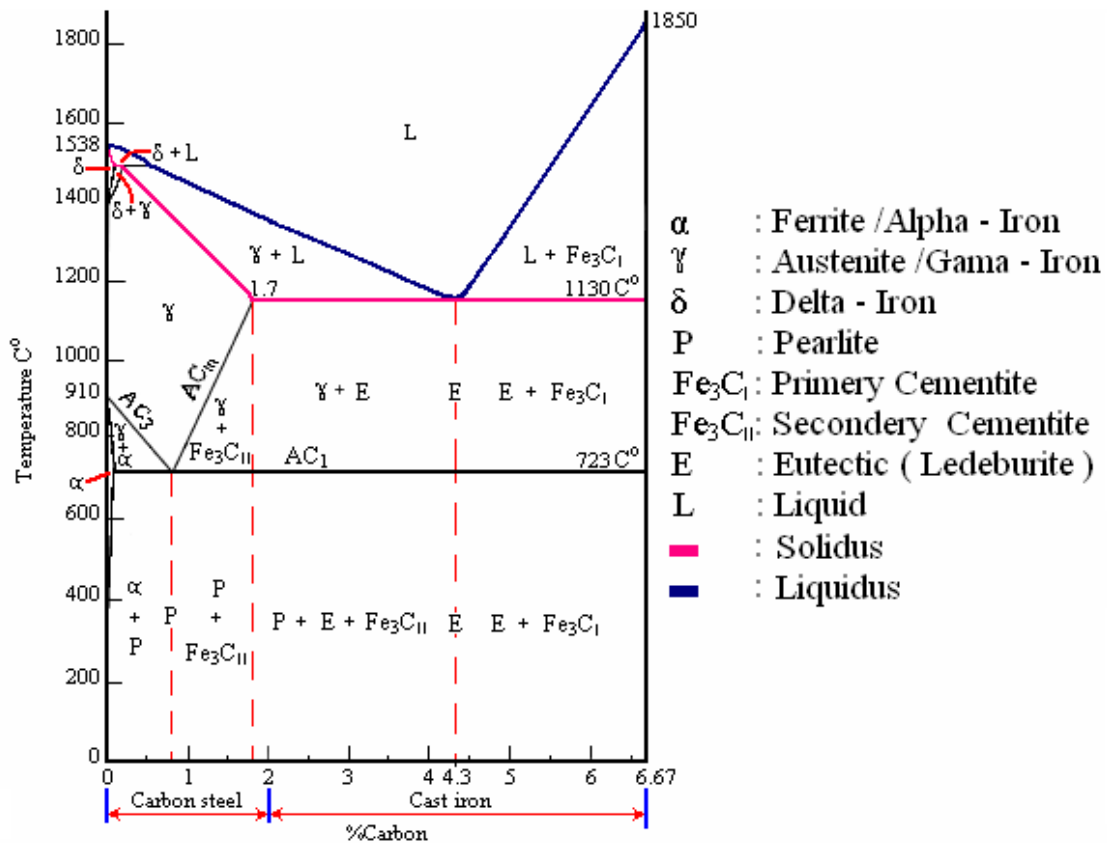


Fig. (5) : Explain the iron - carbide equilibrium phase diagram .

Fig (6) shows an enlarged view of the phase diagram for very low carbon percentage .the solubility of alpha ferrite for carbon decreases as the temperature decreases. When an alloy with less than **0.02% C** is cooled carbon in excess of that which can be held by the alpha ferrite is precipitated as cementite .

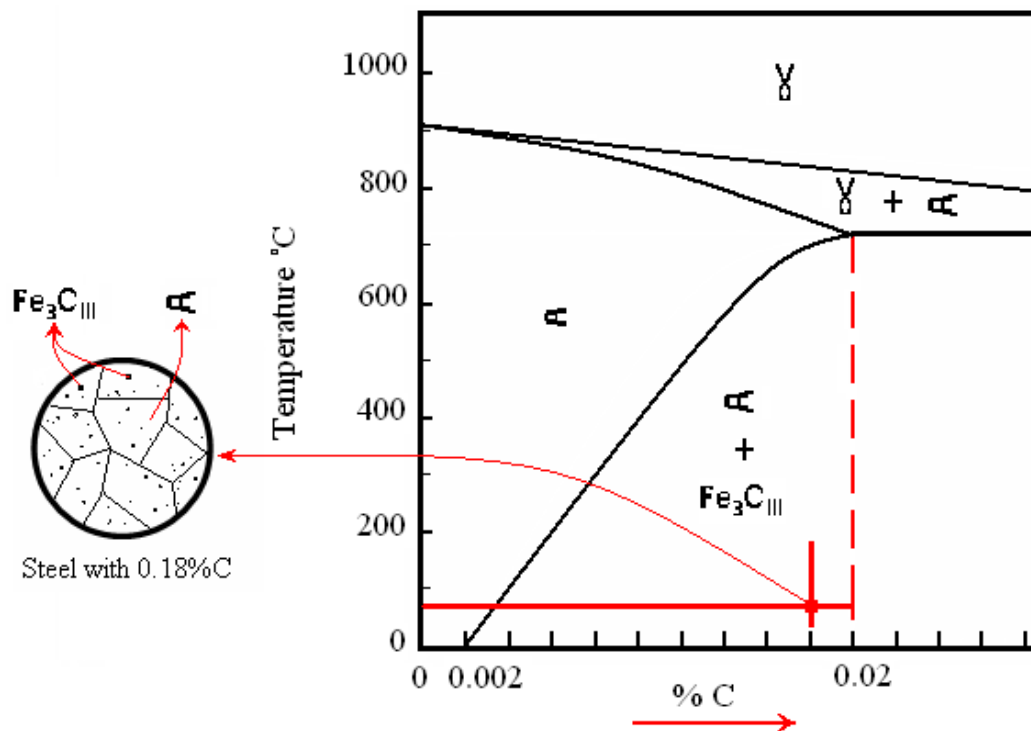


Fig (6) : The microstructure of the steel with very low carbon content .

Fig (7) shows the cooling of a **0.4%C** steel a hypoeutectoid steel from the austenite phase to room temperature .when the alloy is cooled to below about **820°C** ,crystals of alpha ferrite starts to grow in the austenite. The ferrite tends to grow at the grain boundaries of the austenite grains. At **723°C** the remaining austenite changes to the eutectoid structure (pearlite) .the result is a network of ferrite along the grain boundaries surrounding areas of pearlite. When an alloy with **0.8%C** is cooled from the liquid to a temperature above **723°C** ,fig (7), the formed solid is gamma i-e austenite. At **723°C** there is an eutectoid and sudden change to give a laminated structure of alpha ferrite plus cementite (pearlite). Fig (7) also shows the cooling of **1.2%C** steel a hypereutectoid steel ,from the austenite phase to room temperature .

When the alloy is cooled below about **900°C** cementite starts to grow at the grain boundaries of the austenite grains. At **723°C** the remaining austenite changes to the eutectoid structure (i-e pearlite). The result is network of cemenite along the grain boundaries surrounding areas of pearlite . in all the above discussion we have assumed that the cooling from the austenite phase is slow enough for diffusion to occur and all the changes to be completed.

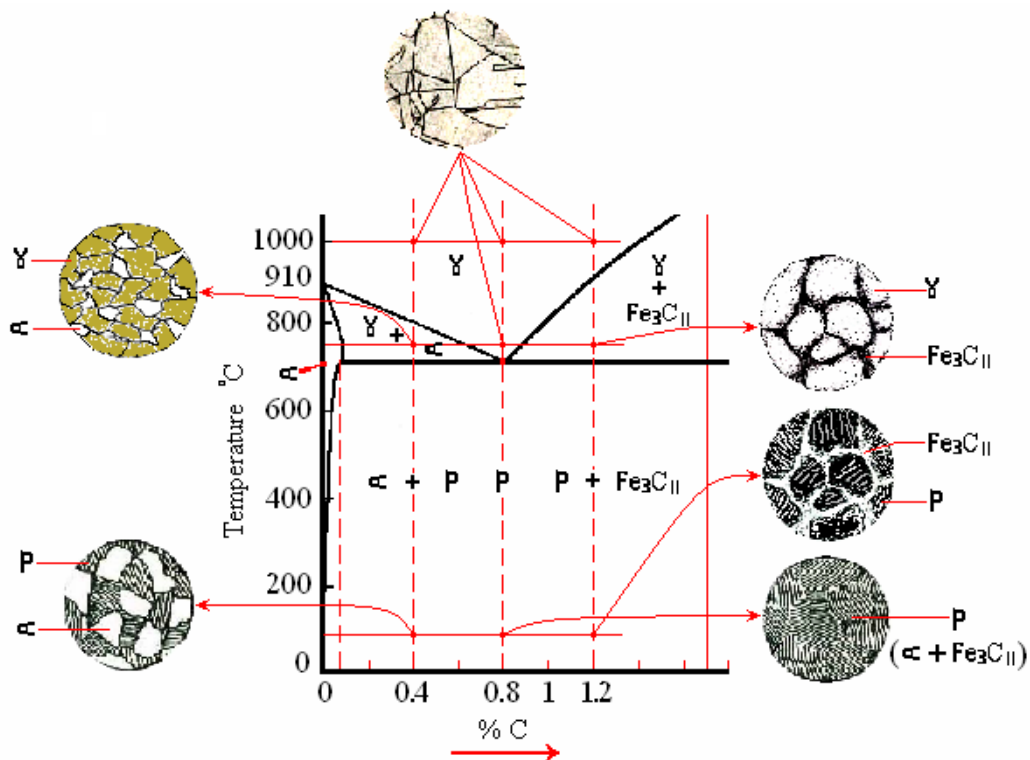


Fig (7) : The effect of cooling on the microstructure of different carbon steel's .

Fig (8) illustrated an enlarged view for the position at which peritectic reaction occur , particularly at temperature **1492 °C** .Where as Delta – iron (**δ**) with (0.09% C) interacts with the remaining liquid (**L**) with

(0.53%C) to transform just below **1492 °C** to a new solid solution known as Gamma – iron (γ) .

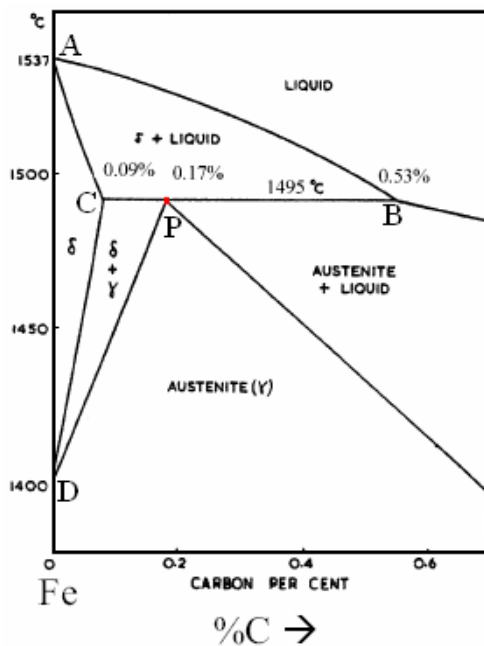


Fig. (8): Explain the occurred following peritectic reaction at point (P) .

$$\delta(0.09 \%C) + L (0.53 \% C) \rightleftharpoons \gamma(0.17\% C)$$

The effect carbon content on the properties :

Fig (9) shows how the percentage of ferrite , pearlite and cementite change with percentage carbon and also how the mechanical properties are related to these changes. For steel cooled slowly from the austenite phase up to eutectoid composition (i-e for hypereutectoid steel) , the decreasing percentage of ferrite and the increasing percentage of pearlite result in an increase in tensile strength and hardness. The ductility deceases, the percentage elongation being a measure of this, for hypereutectoid steels increasing the amount of carbon decreases the percentage of pearlite and increases the percentage of cementite. This increases the hardness but has little effect on the tensile strength, the ductility also changes little.

Disadvantages of plain carbon steel :

- Plain carbon steel have limits on their engineering application because :
1. High strength cannot be obtained with good ductility and toughness .
 2. The severity of water quenching often leads to distortion and cracking of the steel .
 3. Large section cannot be hardened uniformly, because of the deference in the cooling rate across the large section .
 4. These steels have poor resistance to corrosion and oxidation at high temperatures .

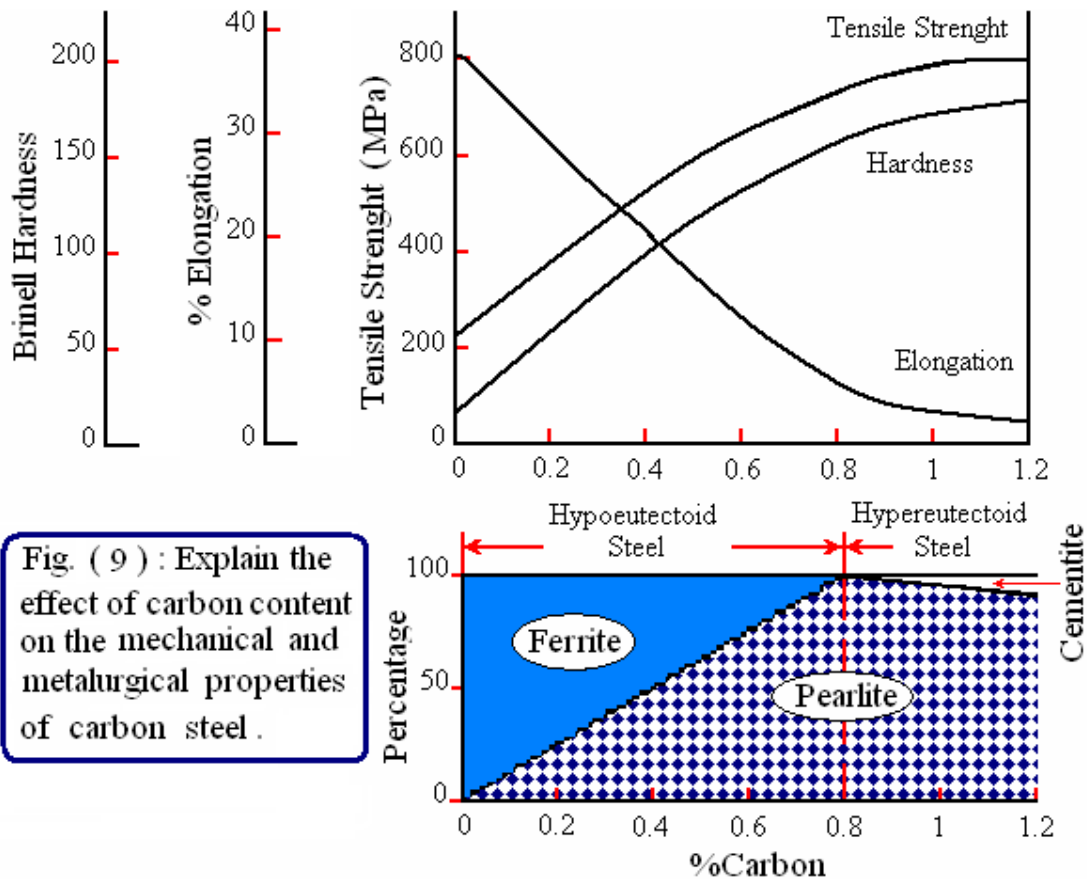


Fig. (9) : Explain the effect of carbon content on the mechanical and metallurgical properties of carbon steel .

Alloy steels :

The term **alloy steel** is used to describe those steels in which one or more alloying elements in addition to carbon have been added in order to modify the properties of the steel. There are number of ways in which the alloying elements can have an effect on the properties, the main one being :

1. Solution hardening the steel .
2. Form carbides .
3. Form graphite .
4. Stabilize austenite or ferrite .
5. Change the critical cooling rates .
6. Improve corrosion resistance .
7. Change grain growth .
8. Improve Macheability (Chip formation) .

Types of alloy steels :

A-High-strength low-alloy structural steel .

- B-Medium-alloy nicked-chromium steels .
- C-Manganese steels .
- D-Maraging steels .
- E- Stainless steels .
 - 1-ferritic steel .
 - 2- martensitic steel .
 - a-stainless iron .
 - b-stainless steel .
 - c-high chromium stainless steel.
- 3-Austenitic steel .
- F-Special purpose steel (heat-resisting steel ,spring steel ,... etc) .

Alloy Steels

Alloy steels are alloys of iron with the addition of one or more of the following elements; carbon, manganese, silicon, nickel, chromium, molybdenum, and vanadium. The alloy steels cover a wide range of steels including low-alloy steels, stainless steels, heat-resistant steels, and tool steels.

Low-Alloy Steels

There is an SAE/AISI four-digit classification system for the low-alloy steels. As in the carbon steels, the first two digits are for the alloy class and the last two (or three digits) are for the carbon content. Because of the various combinations of elements, the system is more extensive than that used for the carbon steels. The general SAE/AISI classification system for low-alloy steels is as follows:

Manganese steels	13xx series
Nickel steels	23xx, 25xx series
Nickel–chromium steels series	31xx, 32xx, 33xx, and 34xx
Molybdenum steels	40xx, 44xx series
Chromium–molybdenum steels	41xx series
Nickel–chromium–molybdenum steels	43xx and 47xx series 88xx 81xx, 86xx, 87xx, and 93xx, 94xx, 97xx, and 98xx
Nickel–molybdenum steels	46xx and 48xx series
Chromium steels	50xx and 51xx series 50xxx, 51xxx, and 52xxx series
Chromium–vanadium steels	61xx series
Tungsten–chromium steels	71xxx, 72xx series
Silicon–manganese steels	92xx
Boron steels	xxBxx series
Leaded steels	xxLxx series

The boron-containing steels are low-alloy steels with boron added in the amount of 0.0005–0.003%. Boron is a strong hardenability element. The leaded steels contain 0.15–0.35% lead for improved machinability (however, lead is no longer favored as an alloying addition because of health concerns). These steels are supplied in the form of bar, plate, and forged products and are usually heat treated to obtain specific mechanical properties, especially high strength and toughness. Mechanical properties of selected SAE/AISI low-alloy steels depend on its processing conditions like as (as-rolled, annealed, normalized and quenched and tempered) conditions. For example, SAE/AISI 4340 steel is usually heat treated by heating the component to 950-1000 °C followed by quenching in oil. The component is then tempered at a temperature between 205-650°C. This nickel-chromium-molybdenum steel in the quenched and tempered condition (tempered at 205°C) can achieve a yield strength of 1675 MPa and a tensile strength of 1875 MPa. Quenched and tempered low-alloy steels are used in a large number of applications requiring high strength and good toughness. In the annealed condition, SAE/AISI 4340 steel has a yield stre

Higher Alloy Steels

Higher alloy steels (usually containing over 8% alloying elements). The higher alloysteels include stainless steels, tool steels, heat-resistant steels, wear resistant steels, and ultrahigh-strength steels.

Tool Steels

Tool steels are alloy steels that are used to cut machine other materials. Tool steels contain various levels of Cr, Ni, Mo, W, V, and Co. The categories of tool steels are:

Type of series	Detailed name of the series
M series	Molybdenum high-speed steels
T series	Tungsten high-speed steels
Cr series	Chromium hot-work steels
H series	Molybdenum hot-work steels
A series	Air-hardening medium-alloy cold-work steels
D series	High-carbon high-chromium cold-work steels
O series	Oil-hardening cold-work steels
S series	Shock-resistant steels
L series	Low-alloy special-purpose tool steels
P series	Low-carbon mold steels
W series	Water-hardening tool steels

The high speed steels are used in high-speed cutting tools such as drill bits. The hot-work tool steels are used in operations that utilize dies for punching, shearing, and forming materials at elevated temperatures, and the cold-work steels are used in similar operations at room temperature.

Stainless Steels:

Stainless steels are corrosion-resistant steels that contain at least 10.5% chromium. Chromium is unique in that it forms a passive layer on the steel surface that provides protection from corrosion. There are basically five types of stainless steels: austenitic, ferritic, duplex, martensitic, and precipitation hardening steels. These five types of stainless steel have a somewhat simplified classification system as follows:

Austenitic stainless steels with low nickel	2xx series
Austenitic stainless steels	3xx series
Ferritic stainless steels	4xx series
Duplex stainless steel	329
Martensitic stainless steels	4xx series
Precipitation strengthening stainless steels	6xx (xx-x PH)

The classification system is different for the stainless steels than the system or SAE/AISI low-alloy steels in that the last two digits (xx) do not represent the carbon content and have no particular compositional meaning. Each type of stainless steel is expanded upon below:

Austenitic Stainless Steels:

Austenitic stainless steels have sufficient alloying to stabilize austenite at room temperature. These steels being are nonmagnetic , have excellent low-temperature toughness, weldability, and corrosion resistance. On the other hand, they have relatively low yield strength and can only be strengthened by cold working the steel, by precipitation hardening or by interstitial or substitutional solid solution strengthening. The 2xx series of austenitic stainless steels, manganese and nitrogen were substituted for the lower nickel level in order to maintain strength. The 3xx series are iron–chromium–nickel alloys that contain 16–26% chromium and 6–22% nickel. The popular type 304 austenitic stainless steel contains 18– 20% Cr and 8–12% Ni and is often referred to as “18 / 8” stainless steel for the chromium and nickel content. The limiting of carbon is important in austenitic stainless steels. When heated, carbon forms chromium carbide that precipitates on the austenite grain boundaries and produces a condition known as *sensitization*. Because the chromium is tied-up as carbide, the chromium adjacent to the boundaries will be depleted in chromium and corrosion can take place. Sensitization is reversible by

heating the steel to temperatures between (1040 and 1150) °C followed by rapid cooling to room temperature. The high temperature dissolves the carbides and the rapid cooling prevents reprecipitation of the carbides. The following list summarizes compositional variations of austenitic stainless steel steels:

Symbol	Detailed title	Symbol	Detailed title	
201	Low nickel replaced with manganese and nitrogen	310	310 Higher Cr and Ni than 309 for improved heat resistance	
202	Higher Mn than 201		310S Lower carbon 310	
			310Cb Niobium (columbium) added	
205	Higher Mn and N than 202	314	Higher Si for improved heat resistance	
301	Lower Ni and Cr to increase work-hardening ability	316	Mo added for improved corrosion resistance	
302	302 General-purpose 18–8 stainless steel	316F	Higher S and P for machinability	
	302 B Scaling resistance improved with Si	316L	Lower C for improved corrosion resistance and weldability	
303	303 Enhanced machinability with a S addition	316LN	Lower C and higher nitrogen (for strength)	
	303Se Improved machined surfaces with a selenium addition	316H	Higher carbon 316	
304	304 Popular 18–8 stainless steel, lower C than 302	316N	Nitrogen added for strength	
	304L Low-carbon 304 for improved corrosion resistance	316Ti	Titanium added	
	304LN Low-carbon 304 with nitrogen added for strength	316Cb	Niobium (columbium) added	
	304H Higher carbon 304	317	317 Higher Cr and Mo for improved corrosion resistance	
	304Cu Copper added for improved cold working		317L	Low-carbon 317 for improved weldability
	304N Nitrogen added for strength		321	Titanium added to minimize Cr carbide precipitation
305	Higher Ni for reduced work hardening	330	High Ni to minimize carburization and improve thermal shock	
308	Higher Cr and Ni for weldability	347	347 Nb and Ta added to minimize Cr carbide precipitation	
309	309 High Cr and Ni for heat resistance		347H	Higher carbon 347
	309S Lower carbon 309	348	348 Ta and Co added for restricted nuclear applications	
	309Cb Niobium (columbium) added		348H	Higher carbon 348
		384	Higher Ni for decreased work hardening	

Ferritic Stainless Steels:

The ferritic stainless steels are basically iron – chromium alloys with chromium ranging from 10.5 to 27%. Nickel is absent in ferritic stainless steels except for minor amounts, i.e., less than 1%, in some alloys. These steels have a microstructure of ferrite at room temperature and are magnetic. Type 409 stainless steel with the lowest chromium level (10.5–11.75%) is the least expensive of the ferritic stainless steel series and is used for automotive exhaust systems because it far outlasts carbon steel in that application. There are fewer variations of ferritic stainless steels than austenitic stainless steels. The ferritic stainless steels are listed below:

Symbol	Detailed name
405	Low Cr with Al added
409	Low Cr, for automotive exhaust applications
429	
430	General-purpose ferritic stainless steel
430F	Free machining with higher S and P
430Se	Selenium added for improved machined surfaces
434	Mo added for improved corrosion resistance
436	Mo, Nb, and Ta added for corrosion and heat resistance
439	Low C, Ti added to minimize sensitization
442	Higher Cr for improved oxide scaling resistance
444	Low C, Mo for corrosion resistance, Ti and Nb for sensitization
446	Highest Cr for improved scaling resistance

Duplex Stainless Steels:

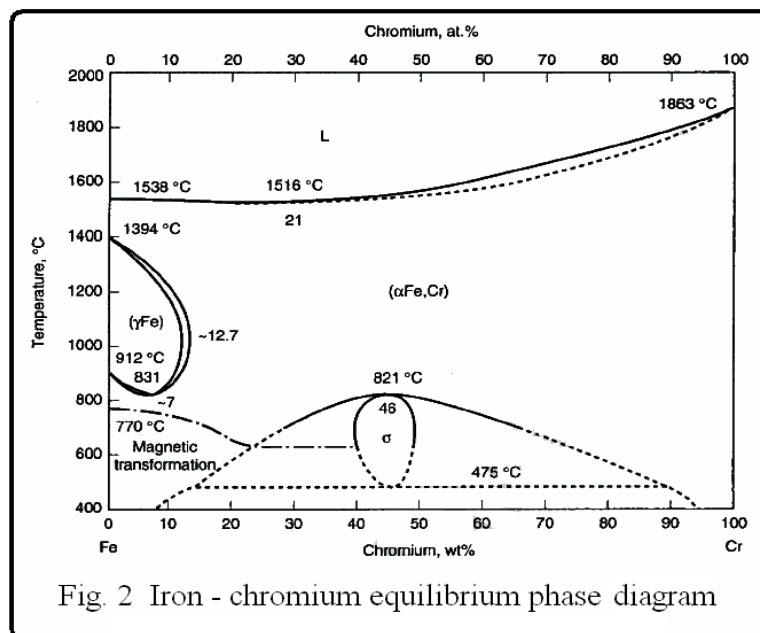
Type 329 is an iron–chromium alloy with 2.5–5% nickel and 1–2% molybdenum that has a mixed (duplex) microstructure of approximately equal percentages of ferrite and austenite. There are many more duplex stainless steels that have priority compositions and trade names. The corrosion characteristics of these duplex stainless steels are similar to austenitic stainless steels. However, they have higher strength and better resistance to stress–corrosion cracking than austenitic stainless steels.

Martensitic Stainless Steels:

To produce martensite in a stainless steel, the alloy must be transformed from the austenite phase field. According to the equilibrium phase diagram, this means that they have restricted chromium levels within the range required to form the gamma loop where austenite exists (see Fig 2.). The gamma loop is the region between 800 and 1400°C and 0 and 12.7% Cr in Fig. 2. Since austenite only exists in this restricted region, the steel must be heated within this temperature range and quenched to room temperature to form martensite. Martensitic stainless steels contain

added carbon, which expands the gamma loop to allow higher chromium contents to be used. Because they can be heat treated, the martensitic stainless steels generally have higher strength than the austenitic and ferritic stainless steels. The martensitic stainless steels are listed below:

Symbol	Detailed name
403	Select quality for highly stressed parts
410	General-purpose martensitic stainless steel
414	Ni added for improved corrosion
416	Higher P and S for improved machinability
416Se	Se added for improved machined surfaces
420	Higher C for increased strength
420F	Free machining with higher P and S
422	Mo, V, and W added for increased strength and toughness
431	Higher Cr, Ni added for improved corrosion resistance
440	A Highest Cr, C added for increased hardness
440B	Highest Cr, more C added for increased hardness/toughness
440	C Highest Cr, highest C for increased hardness/toughness
501	Low Cr, Mo added
502	Low C, Mo added



Non- Ferrous Alloy's

Non- Ferrous alloys are those alloys which do not have iron as their base element. The following are some of non- ferrous alloys:-

Light alloys :-

They have low density from about 1.7 to 4.5 kg / cm³ with zinc alloys about 6.06 Mg / m³.

- A- Aluminum alloys.
- B- Magnesium alloys.
- C- Titanium alloys.
- D- Zinc alloys.

Heavy alloys :-

They have higher density about 8.8 kg / cm³ .

- A- Copper alloys.
- B- Nickel alloys.
- C- Cobalt alloys.

The advantages of non- ferrous alloy's over ferrous metals:-

- 1- Good resistance to corrosion without special processes having to be carried out.
- 2- Generally much lower density and hence lighter weight components can be produced.
- 3- Often lower melting points and so casting is easier.
- 4- Often greater ductility and so cold-working processes are easier.
- 5- Higher thermal and electrical conductivities.

The advantages of ferrous method over non-ferrous alloys:-

- 1- Generally greater strengths.
- 2- Generally greater stiffness (Larger values of the modals of elasticity).
- 3- Better for welding.

Aluminum:

Introduction:

Aluminum performs well in both mechanical and electrical applications. For mechanical applications:

- 1-Aluminum can provide a high strength to weight ratio.
- 2-Ease of manufacture of complex shapes.
- 3-Excellent resistance to corrosion..
- 4-Aluminum is a good conductor of heat and electricity (approximately 65% of the conductivity of electrical standard copper).
- 5-It is non-magnetic and non-sparking.
- 6-Aluminum is also non-combustible.
- 7-It is non-toxic.
- 8-Can is highly reflective.
- 9-It is impermeable to liquids and air.
- 10- Aluminum has a very low density (2.7 gm/ cm^3) metal that can be alloyed with a number of different elements.

Aluminum's resistance to corrosion is a result of a microscopic oxide coating which is formed on contact with air. This layer can be easily removed as its structure does not provide much mechanical strength. If the material is anodized, a harder more dense oxide layer is created which is more resistant to abrasion. Aluminum can be easily extruded, rolled, cast and machined. Extruded products include bars, tubes and special sections. Rolled products include foil, sheet and plate. The two main types of casting processes are sand and die casting to provide a wide range of different physical properties. Alloys of

aluminum can possess significantly increased strength, ductility and actability, especially after heat-treatment processes. Also, aluminum is often used as an electrical conductor. The international classification of Aluminum Alloys follows as shown below.

Wrought Alloys

- 1XXX Aluminum of 99% minimum purity
- 2XXX Aluminum and Copper alloys
- 3XXX Aluminum and Manganese alloys
- 4XXX Aluminum and Silicon alloys
- 5XXX Aluminum and Magnesium alloys
- 6XXX Aluminum, Magnesium and Silicon alloys
- 7XXX Aluminum, Zinc and Magnesium alloys
- 8XXX Miscellaneous alloys, e.g. Aluminum-Lithium alloys

Cast Alloys

- 1XX.X Aluminum of 99% minimum purity
- 2XX.X Aluminum and copper alloys
- 3XX.X Aluminum, Silicon and Copper & / or Magnesium alloys
- 4XX.X Aluminum and Silicon alloys
- 5XX.X Aluminum and Magnesium alloys
- 6XX.X Unused Classification
- 7XX.X Aluminum and Zinc alloys
- 8XX.X Aluminum and Tin alloys
- 9XX.X miscellaneous alloys

Cast alloys generally contain a higher proportion of alloying elements than wrought alloys. The presence of manufacturing defects reduces the strength and strain properties of cast alloys. The performance of the alloys can be varied through the use of a variety of techniques, either individually or in combination. These techniques include strain hardening, heat treating, annealing, work hardening and precipitation hardening.

Heat treatable wrought Alloys:

2XXX – Aluminum & Copper Alloys

6XXX – Aluminum, Magnesium & Silicon Alloys

7XXX – Aluminum, Zinc & Magnesium Alloys

Heat treatable Casting Alloys:

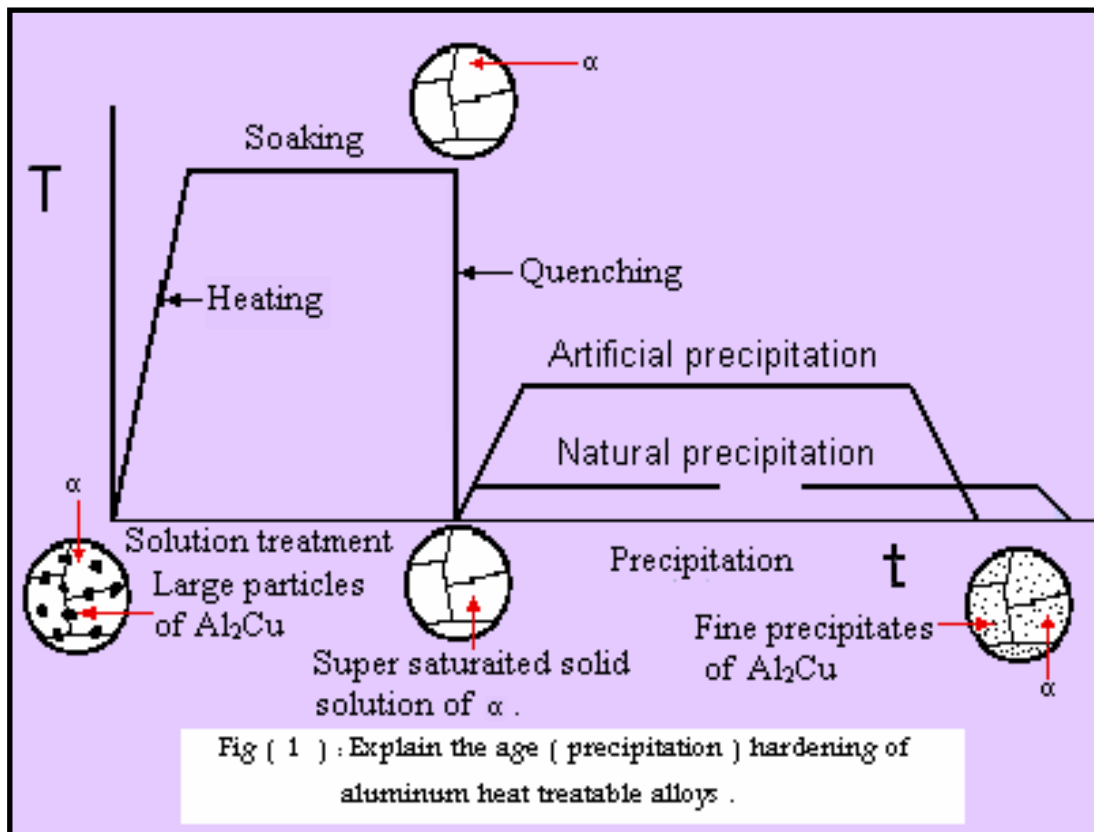
2XX.X – Aluminum & Copper Alloys

3XX.X – Aluminum, Silicon and Copper and/or Magnesium alloys

7XX.X – Aluminum & Zinc Alloys

Age (precipitation) hardening process:

1. Solution treatment at single phase region.
2. Quenching (rapid cooling) by water.
– Super saturated solid solution (e.g. of Cu in α – Al).
3. Controlled decomposition of super saturated solid solution into fine precipitates of the second phase (Al_2Cu) by natural aging (precipitation) which occur in several months at room temperature , or by acceleration the precipitation process by heating the solution treated alloy at higher temperatures (165 – 180) °C for a few hours (8 – 10) hr. then followed by air cooling . This treatment is well defined by observing the fig. (1).



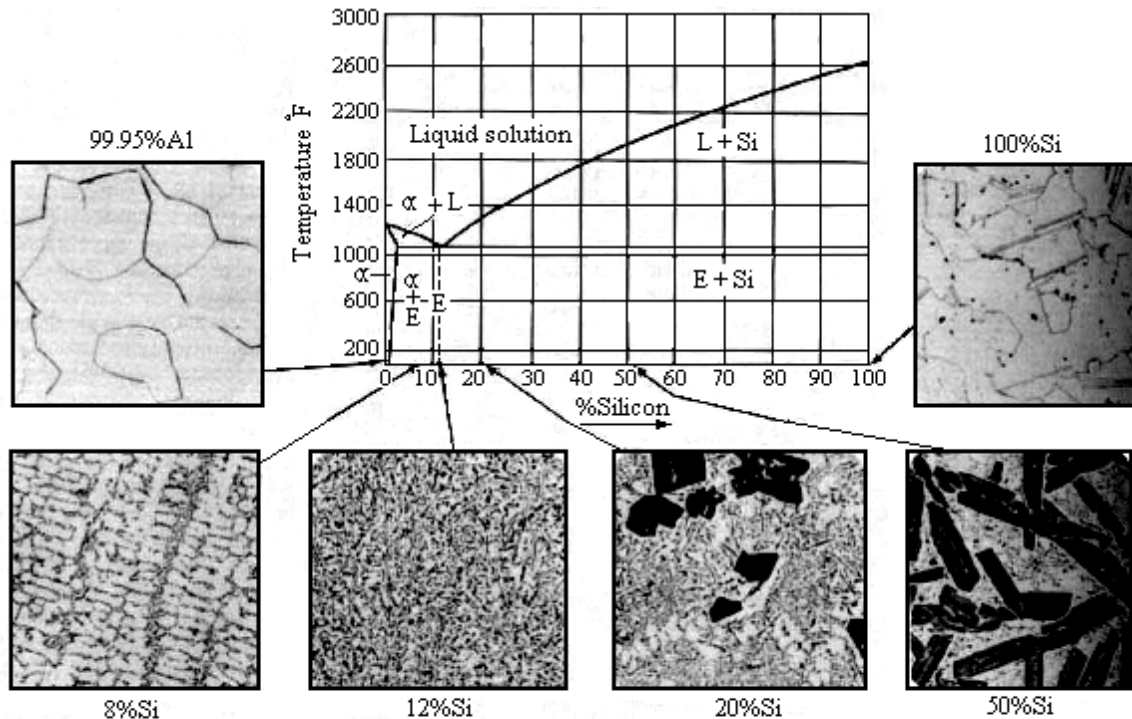
Aluminum – Silicon casting Alloys :

Aluminum alloys are grouped according to the major alloying elements they contain. The 4XXX group is alloyed with silicon for ease of casting. Silicon is good in metallic alloys used for casting. This is because:

- 1- Increases the fluidity of the melt.
- 2-Reduces the melting temperature.
- 3-Decreases the contraction associated with solidification.
- 4-It is very cheap as a raw material.
- 5-Silicon also has a low density (2.34 g / cm^3), which may be an advantage in reducing the overall weight of the cast component.
- 6-Silicon has a very low solubility in aluminum; it therefore precipitates as virtually pure silicon, which is hard and hence improves the abrasion resistance.

Aluminum-silicon alloys form a eutectic at 11.7 wt% silicon, the eutectic temperature being $577 \text{ }^\circ\text{C}$. This represents a typical composition for a casting alloy because it has the lowest

possible melting temperature. Al-12Si wt% alloys are therefore common. The phase diagram of binary Aluminum - Silicon alloys is illustrated in fig. (2).



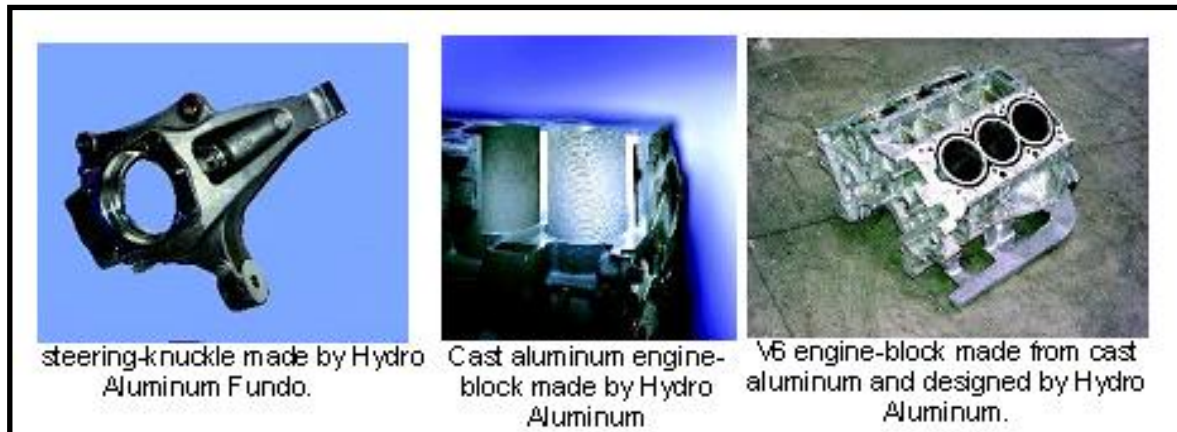
Fig(2) : Explain the phase diagram of Aluminum - Silicon binary alloys and typical microstructures at room temperature .

A typical chemical composition (wt %) for an alloy used in the manufacture of an engine-block is as follows::

Si	Cu	Mg	Fe	Mn	Ti	Sr	Zr
7-8	3-4	0.25-0.35	0.0-0.4	0.5	0.00-0.25	trace	0.25

The copper is used for precipitation hardening (Al_2Cu , $Al_5Mg_8Cu_{26}$), should that be necessary. Iron is to be avoided if possible, since it can form plate-like precipitates (Al_5FeSi) which embitters the casting and can block the flow of liquid metal in the mould. The strontium, when added deliberately, helps to modify the shape of the silicon, rather as does sodium. Strontium is preferred to silicon, because the effects of sodium fade relatively rapidly when the liquid metal is held at temperature for a prolonged period before solidification. On the other hand, strontium, by a variety of mechanisms, introduces a greater degree of porosity in the final casting. The following

images are of cast aluminum automobile components, provided by the Institute of Cast Metals Engineers.



Alloys ideal for electronics :

A new range of Si /Al alloys containing up to 70 wt% silicon has been developed using spray forming technology. The alloys are 15% lighter than pure aluminum; they have a low, controlled thermal expansion coefficient, a high stiffness and high thermal conductivity. They are non-toxic, readily machinable, easily plated with nickel, gold, silver or copper.

Copper:

Properties of copper:

1- High electrical conductivity: Pure copper has a high electrical conductivity and so is widely used for electrical conductors. The conductivity increases with purity.

2- High thermal conductivity: Copper is used in radiators, heat exchangers and boiler tubes where heat energy has to be transmitted efficiently. Cu alloys resist fouling in sea water and so are especially useful for heat exchangers using sea water.

3- Good corrosion resistance: In water: Therefore copper is used in environments containing sea water or tap water and in the brewing and chemical industries. In air: Cu corrodes slowly, forming a protective green 'patina' on the surface.

4- High ductility: This is useful because copper can be drawn into wire for electrical applications. It can be made into tubing, which can be easily bent for water supplies.

5- Copper is easily joined by brazing and soldering.

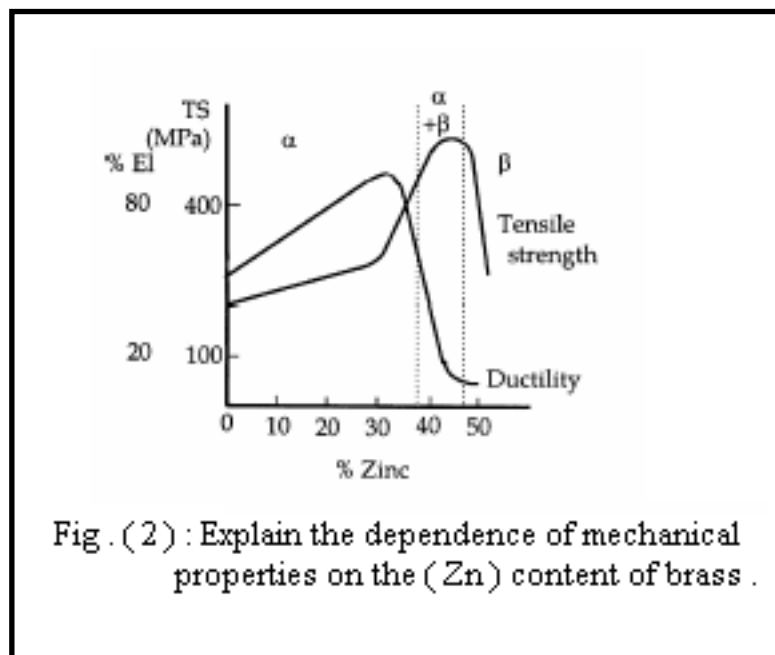
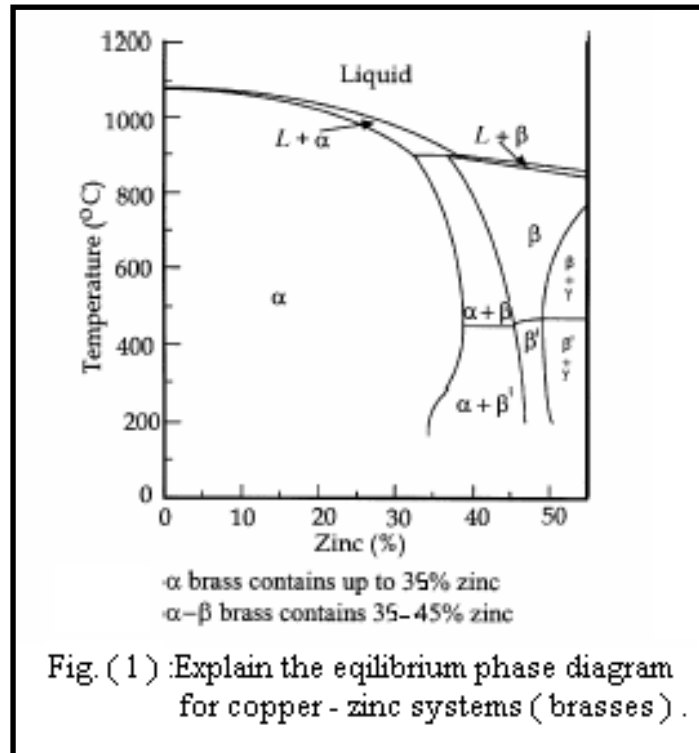
6- Copper has low strength and hardness and so needs to be alloyed for applications where the applied stress is significant.

A. Copper–zinc alloys (brasses):

Brasses

have good corrosion resistance and are suitable for decorative finishes. The two common types are α - β brasses which contains up to 35% zinc, The thermal equilibrium for copper–zinc systems is illustrated in Figure (1).

Brasses fall into two categories, which are determined by the nature of the phases formed in the metal at room temperature and therefore their properties. **First**, α -brasses are those that form a single phase. Their strength increases as the zinc content is increased because of solute hardening. Ductility increases to a maximum at 30% zinc as illustrated in Figure (2).

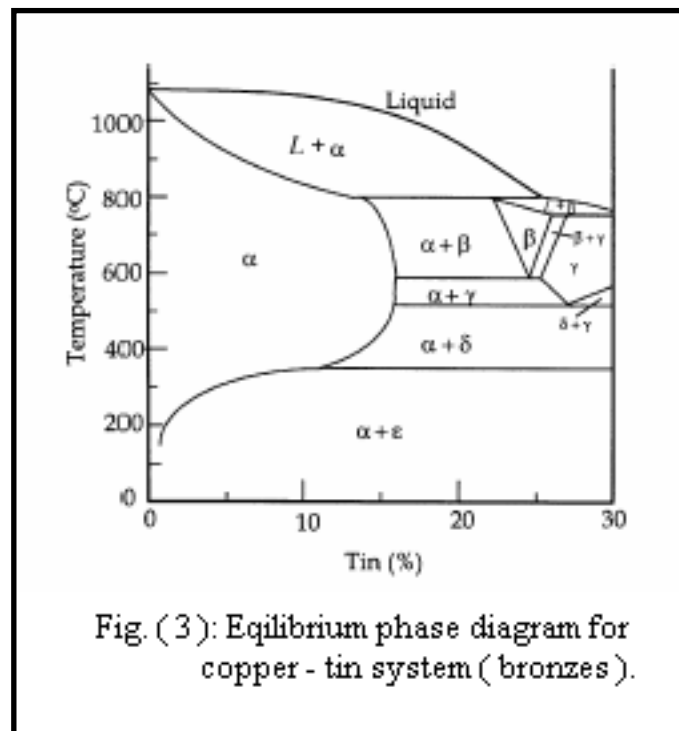


A well-known form called **cartridge brass** consists of 30% Zn in copper. Copper with 35% Zn is more widely used because it is cheaper. Typical uses include condenser tubes and decorative components made by deep drawing. The **second** category is called **α - β brass**. They are stronger than **α -brass**

but have low ductility as can be seen in Figure (2) . The corrosion resistance is also reduced. Copper with 40% zinc is called **Muntz metal**. It gives a widmanstatten structure on casting because α precipitates from β (see phase diagram). This tends to be brittle. Hot working breaks up the widmanstatten structure and makes the alloy tougher. It will also be anisotropic. β which is a disordered solid solution, may change to β' , an ordered solid solution, on very slow cooling. Typical uses of **Muntz metal** include condenser and heat exchanger plates. **Free cutting brass** can be made by the addition of 2% lead to brasses. **High tensile brasses** contain small additions of manganese, tin, aluminum or iron to increase strength and corrosion resistance. A ship's propeller is an example of a high tensile brass.

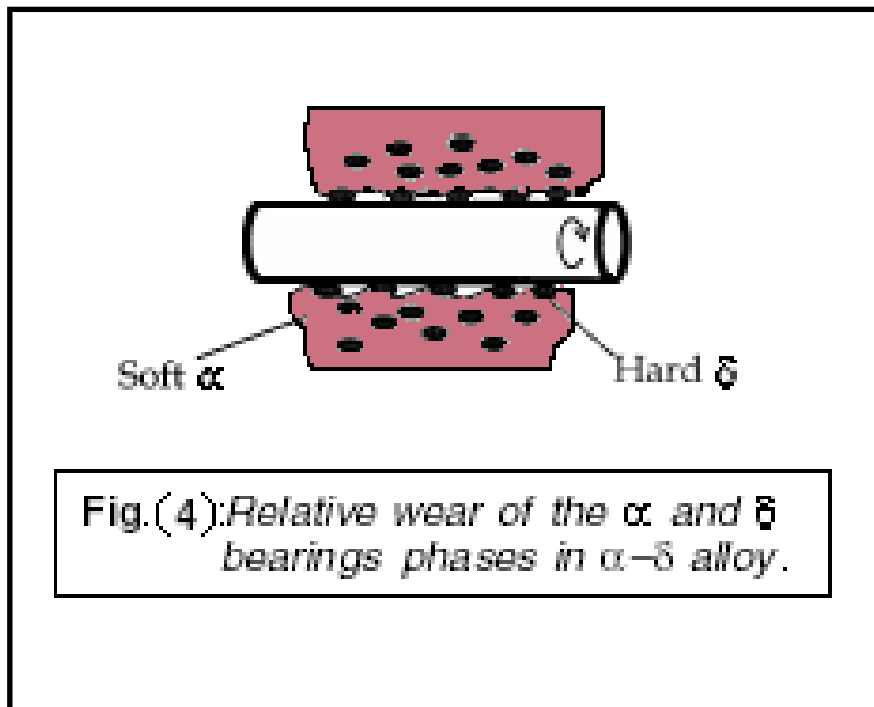
B. Copper–tin alloys (tin bronzes):

The addition of tin to copper produces the valuable class of materials known as bronzes. Their thermal equilibrium diagram is illustrated in Figure (3)



The α bronzes are ductile and have better strength and corrosion resistance than brass. They are, however, more expensive. Five per cent Sn in copper is used for springs and steam turbine blades. Three per cent Sn and 1.5% Zn added to copper is used for so-called ‘copper’ coins. α - δ alloys can be cast to make bearings. In use, the soft phase wears away leaving the hard δ phase to support the rotating journal. The δ provides good wear resistance. The gaps where the α has worn away provide channels for good oil flow and retention Figure (4).

The ductile α provides good shock resistance. Many bronzes contain some phosphorus. They are then called **phosphor bronzes**. The phosphorus forms copper phosphide (Cu_3P). This is a hard phase which improves the wear resistance of bearings because it acts like the δ phase. α - δ bronzes containing some zinc are called **gun metals**. They are used for pumps and valves operating at high pressures. **Leaded bronze** is also an important type. Lead can be added to Tin – bronzes up to 2.0% in order to improve its machinability



C. Copper–aluminum alloys (aluminum bronzes) :

D. Copper–Nickel alloys :

E. Heat-treated (precipitation hardening) Cu-alloys:

- **Beryllium bronze.**
- **Chromium copper .**
- **Zirconium copper .**
- **Titanium copper.**

CORROSION

WHY STUDY *Corrosion and Degradation of Materials*?

With a knowledge of the types of and an understanding of the mechanisms and causes of corrosion and degradation, it is possible to take measures to prevent them from occurring. For example, we may change the nature of the environment, select a material that is relatively nonreactive, and/or protect the material from appreciable deterioration.

INTRODUCTION

Deteriorative mechanisms are different for the three material types. In metals, there is actual material loss either by dissolution (**corrosion**) or by the formation of nonmetallic scale or film (**oxidation**). Ceramic materials are relatively resistant to deterioration, which usually occurs at elevated temperatures or in rather extreme environments; the process is frequently also called corrosion. For polymers, mechanisms and consequences differ from those for metals and ceramics, and the term **degradation** is most frequently used. Polymers may dissolve when exposed to a liquid solvent, or they may absorb the solvent and swell; also, electromagnetic radiation (primarily ultraviolet) and heat may cause alterations in their molecular structures.

Corrosion of Metals

Corrosion is defined as the destructive and unintentional attack of a metal; it is electrochemical and ordinarily begins at the surface. The problem of metallic corrosion is one of significant proportions; in economic terms, it has been estimated that approximately 5% of an industrialized nation's income is spent on :

- 1- Corrosion prevention and the costly maintenance or replacement of products
- 2- Loss or contamination of product as a result of corrosion reactions.
- 3- Plant shutdowns, waste of valuable resources,
- 4- Reduction in efficiency,
- 5- Expensive overdesign;

Corrosion processes are occasionally used to advantage. For example, etching procedures make use of the selective chemical reactivity of grain boundaries or various microstructural constituents.

Failure criteria

Vary according to circumstances and include:

1. Loss of strength inducing failure of stressed metal parts.
2. Corrosion product contamination of sensitive material, e.g., food or paint.

3. Perforation by pitting corrosion, opening leaks in tanks or pipes.
4. Fracture by environmentally sensitive cracking.
5. Corrosion product interference with thermal transfer.
6. Loss of aesthetic appeal.

The Cost of Corrosion

Cost of loss of product

Cost of reduction of efficiency

Cost of product contamination

Cost of maintenance of standby plant and equipment

Cost of general losses (The indirect consequential losses resulting from corrosion)

Costs associated with design

Costs associated with novel solutions

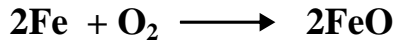
Methods of Approach to Corrosion Phenomena

The effective use of metals as materials of construction must be based on an understanding of their physical, mechanical and chemical properties. These cannot be divorced from the environmental conditions prevailing. Any fundamental approach to the phenomena of corrosion must therefore involve consideration of the structural features of the metal, the nature of the environment and the reactions that occur at the metal/environment interface. The more important factors involved may be summarized as follows:

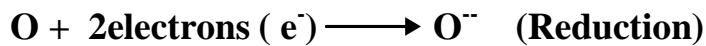
1. ***Metal-*** composition, detailed atomic structure, microscopic and macroscopic heterogeneities, stress (tensile, compressive, cyclic), etc.
2. ***Environment*** - chemical nature, concentrations of reactive species and deleterious impurities, pressure, temperature, velocity, impingement, etc.
3. ***Metal/environment interface*** - kinetics of metal oxidation and dissolution, kinetics of reduction of species in solution; nature and location of corrosion products; film growth and film dissolution, etc.

Oxidation or dry corrosion:

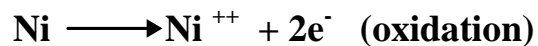
The metals of group 1 and 2 of the periodic classification react readily with oxygen so that, apart from beryllium and magnesium which are useful because of their very low specific gravities combined with good strength, they are of little use as materials in constructional engineering. Most of engineering metals are to be found in the transition group where affinity for atmospheric oxygen is rather less. Oxidation of many of these metals is extremely slow at ambient temperature but occurs much more rapidly as the temperature rises as is demonstrated by the scaling of steel at red. When iron is heated in atmospheric containing available oxygen it becomes coated with a layer of black oxide scale, FeO



The above equation is only a simplified way of expressing the reaction . In fact atoms of iron have been oxidized whilst atoms of oxygen have been reduced. These processes are related to a transfer of electrons from atoms of iron to atoms of oxygen :



The terms ‘**oxidation**’ and ‘**reduction**’ have a wider meaning in chemistry and involve reactions in which oxygen takes in part. Thus, sulphur gases will attack nickel alloys at high temperatures giving rise to intercrystalline corrosion by the formation of nickel sulphide films. In this instance nickel has been ‘**oxidized**’ even though the element oxygen is not involved:



Consequently, in it wider sense, oxidation can be described as a process where the atom involved *losses electrons*; whilst reduction can be described as a process where the atom *gains electrons*.

Affinity for oxygen is not the sole criterion affecting the rate at which a metal oxidizes. Although aluminum has a very high affinity for oxygen it is never the less corrosion resistant. This is due largely to the dense and impervious nature of oxide film which forms on the surface and so protects it from further attack. The extent to which an oxide film will protect the metal beneath depends upon two factors:

(i) The continuity of the film and how effectively it bonds to the metallic surface . Some films are porous and offer poor protection whilst others crack or peel away with repeated heating and cooling of the metal . Such metals and alloys oxidize progressively.

(ii) The mobility of metal and non-metal ions within the oxide film.

Iron at a high temperature will continue to oxidize even though coated with an oxide skin. Iron atoms at the metal interface ionize (Fig 1) , releasing electrons which travel quickly to the surface of the scale. There the electrons react with oxygen from the air forming ions, O^- . These oxide ions are then attracted towards the oppositely-charged Fe^{++} ions. Although the equilibrium composition of the oxide skin is Fe^{++}O^- that

near the metal surface will contain an excess of Fe^{++} ions and that adjacent to the atmosphere will contain more O^{--} ions. The rate at which new ions form depends upon their mobility's within the oxide film That is, new Fe^{++} ions will form as existing ones diffuse away from the metal surface towards O^{--} ions. The more rapidly Fe^{++} ions move away, the more rapidly will atoms ionize to produce new Fe^{++} ions. Prolonged heating of large steel ingots for hot rolling produces a very thick layer of scale. The concentration gradients of Fe^{++} and O^{--} ions within this layer are often so great that three separate crystalline zones are found in the layer. The thin zone adjacent to the metal surface is of basic composition, FeO , whilst that in contact with the atmosphere is of composition Fe_2O_3 . Between the two is a zone containing the intermediate oxide Fe_3O_4 —or $\text{FeO} \cdot \text{Fe}_2\text{O}_3$.

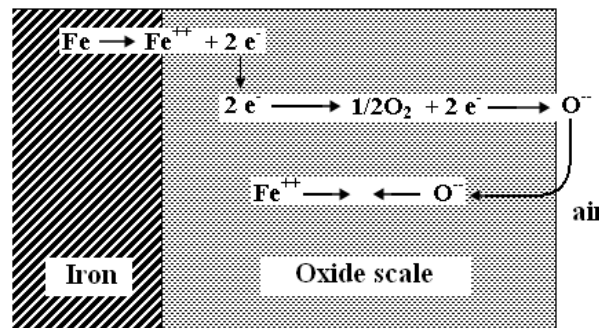


Fig (1): Explain the oxidation of iron

When two steel surfaces are in contact under fairly high pressure and at the same time subjected to alternating or vibrational stresses, fretting corrosion may occur. Differences in elastic properties between the surfaces may lead to localized welding of contacting high spots. The welds subsequently rupture and local high temperatures, set up as a result of friction, cause oxidation of the surface. Fretting is indicated by the presence of a reddish-brown powdery deposit of oxide, Fe_2O_3 , sometimes referred to as **cocoa powder**. This is highly abrasive and so accelerates the attack. Fretting is prevalent in wire ropes and occurs in splines and other press-fitted components which are subjected to alternating stresses. In addition to general wear, such corrosion can lead to the initiation of fatigue cracks particularly since the affected components are subjected to vibrational stresses. Though difficult to eliminate completely it can be minimized by excluding air by the use of a high-pressure grease or by the use of a solid high-pressure lubricant such as molybdenum disulphide

As indicate above oxidation in industrial atmospheres is rarely a simple process involving oxygen only. Contaminants such as carbon dioxide, carbon monoxide, sulphur dioxide , oxides of nitrogen and water vapour

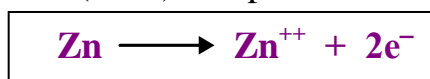
are frequently responsible for the very rapid deterioration of metals at high temperatures .

Under varying conditions carbon dioxide can promote both oxidation and carburization in alloys. This phenomenon leads to **green rot** in Nimonic alloys precipitation of Cr_{23}C_6 leaves the matrix so depleted in protective chromium that extensive oxidation of the nickel to green **NiO** occurs rapidly.

Nimonic and other nickel-base super alloys are rapidly attacked in the presence of sulphur-rich combustion gases. This leads to the formation of black **NiS** so that the effect is aptly described as **black plague**. Solid ash from burning fuel, carried in the combustion gas stream, can also react chemically with surface oxide products. As result a fluxing action may take place resulting in the formation of fluid product at temperatures above **650°C**. Fluid glassy slogs so formed dissolve oxides rapidly so that a metallic surface is exposed to further oxidation. The very rapid corrosion of **Fe-Ni-Cr alloys** which occurs under such condition is known as **catastrophic oxidation**.

Electrolytic Action or Wet Corrosion Involving Two Dissimilar Elements:

Electrolytic action in one form or another is responsible for the bulk of corrosion which occurs in metal at ambient temperatures .In this particular instance it will occur when two dissimilar metal of different '**electrode potential** ' are in electrical contact with other and with an '**electrolyte**' . The term '**electrolyte**' describes some substance which contains both positively- and negatively-charged ions, able to move about freely within it. Much of this chemical action is similar to that which occurs in a simple **Galvanic cell** (fig. 2), consisting of a copper plate and a zinc plate, immersed in dilute sulphuric acid (the electrolyte). When the external circuit is closed a current begins to flow through the ammeter. This current is composed of electrons which are released in the zinc plate and, as their concentration builds up there, are forced to flow to the copper plate. As a result of the loss of electrons zinc atoms become zinc ions (Zn^{++}) and pass into solution in the electrolyte:



As the electrons , which have been forced round the external circuit by pressure of numbers, collect on the copper plate it become negatively charged so that hydrogen ions (H^{+}) , present in the electrolyte form ionized sulphuric acid , are attracted to the copper plate where they

combine with the available electrons to form ordinary atoms and, hence molecules of hydrogen so that bubbles of the gas form on the copper plate :

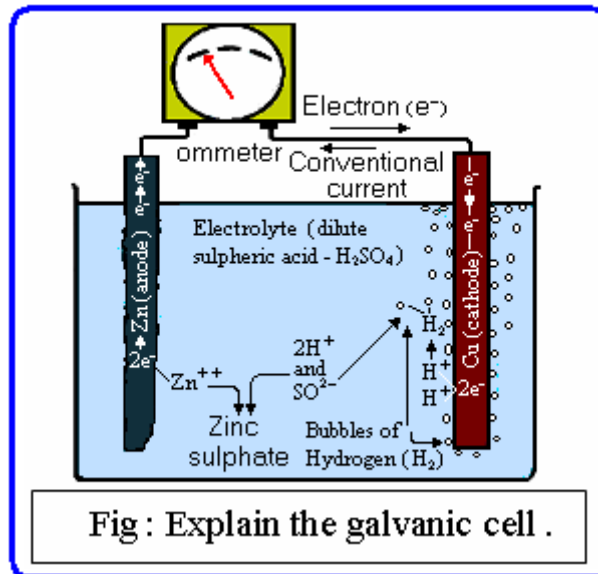


Fig (1): Explain the galvanic cell.

Corrosion Forms:

The different forms of corrosion represent corrosion phenomena categorized according to their appearance and they are as follow:

- 1-Uniform corrosion
- 2- Pitting
- 3- Crevice corrosion
- 4-Film corrosion
- 5-Galvanic corrosion
- 6- Erosion corrosion
- 8-Cavitation
- 9-Fretting corrosion
- 10-Intergranular corrosion
- 11-Exfoliation
- 12-Dealloying (selective leaching)
- 13-Stress corrosion cracking (SCC)
- 14- Corrosion fatigue
- 15-Hydrogen embrittlement

1- Uniform Corrosion :

Uniform corrosion is characterized by corrosive attack proceeding evenly over the entire surface area, or a large fraction of the total area. General thinning takes place until failure. This is the most important form of corrosion. However, uniform corrosion is relatively easily measured and predicted, making disastrous failures relatively rare. Uniform corrosion may add color to a surface. Two classics in this respect are the patina created by naturally tarnishing copper roofs and the rust hues produced on weathering steels. The breakdown of protective coating systems on structures often leads to this form of corrosion. Dulling of a bright or polished surface, etching by acid cleaners, or oxidation (discoloration) of steel are examples of surface corrosion. Corrosion resistant alloys and stainless steels can become tarnished or oxidized in corrosive environments. Surface corrosion can indicate a breakdown in the protective coating system. If surface corrosion is permitted to continue, the surface may become rough and surface corrosion can lead to more serious types of corrosion. The fig. (1) explain some types of uniform corrosion .

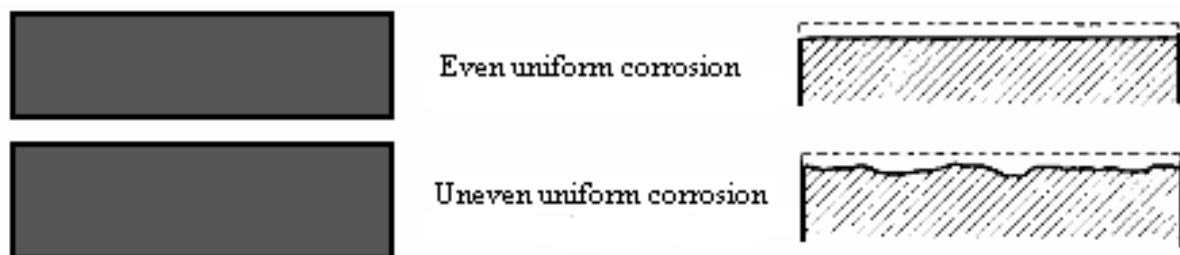


Fig. (1) : Explain the types of uniform corrosion .

Prevention or control of corrosion can usually be achieved by

- 1-Using of a suitable material of construction.
- 2-Using of proper design and installation techniques .
- 3-Modification of the environment by using inhibitors.
- 4-Using protective coatings.
- 5-Using anodic and cathodic protection.